Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the U.S.

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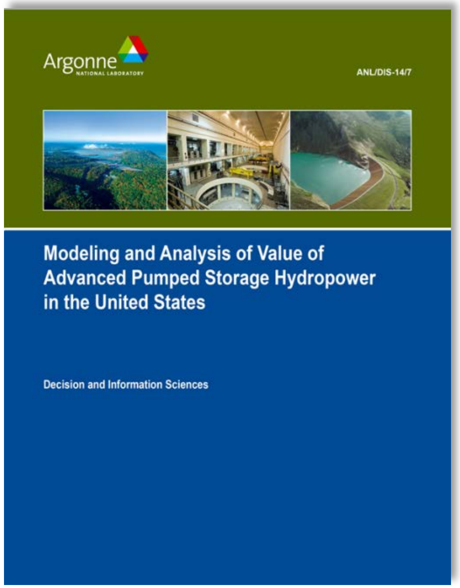


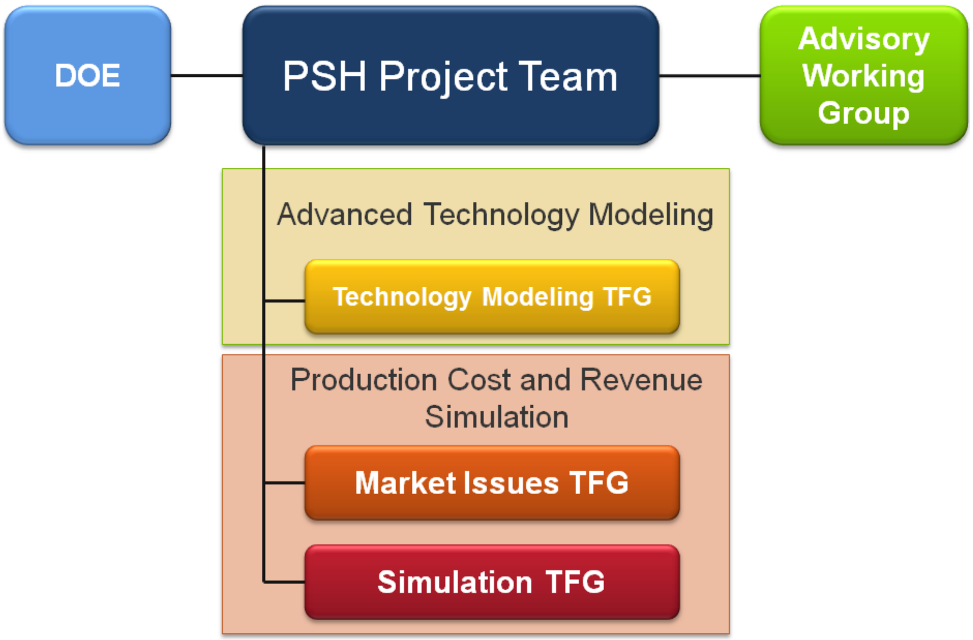
Project Overview & Objectives

- Argonne-led study funded by the USDOE/EERE Water Power Program:

Argonne NATIONAL LABORATORY | SIEMENS | Energy Exemplar | MWH | NREL NATIONAL RENEWABLE ENERGY LABORATORY

Main Objectives:

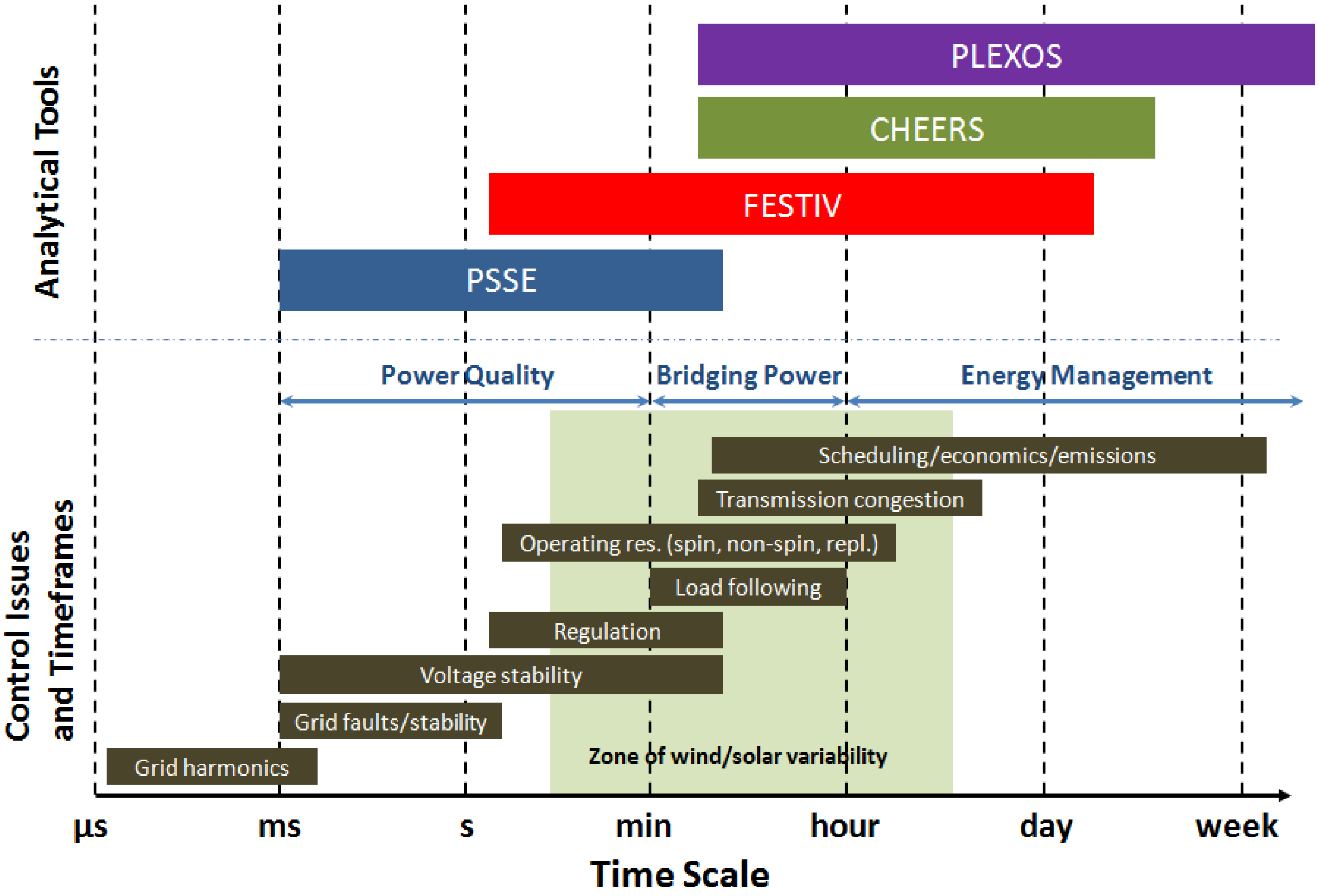
- Improve modeling representation of advanced PSH plants
- Quantify their capabilities to provide various grid services
- Analyze the value of these services under different market conditions and levels of variable renewable generation
- Provide information on full range of benefits and value of PSH



Project website: http://www.dis.anl.gov/psh

Analysis Addressed Wide Range of Operational Issues & Timeframes

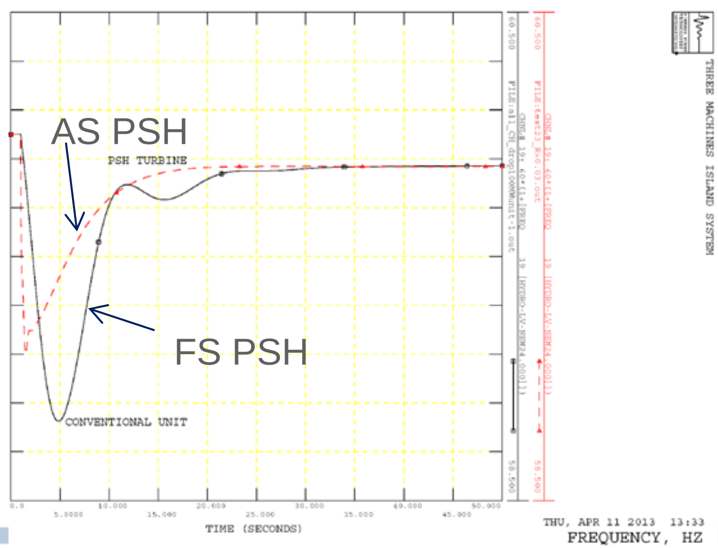
- Analysis aimed to capture PSH dynamic responses and operational characteristics across different timescales, from a fraction of a second to days/weeks.



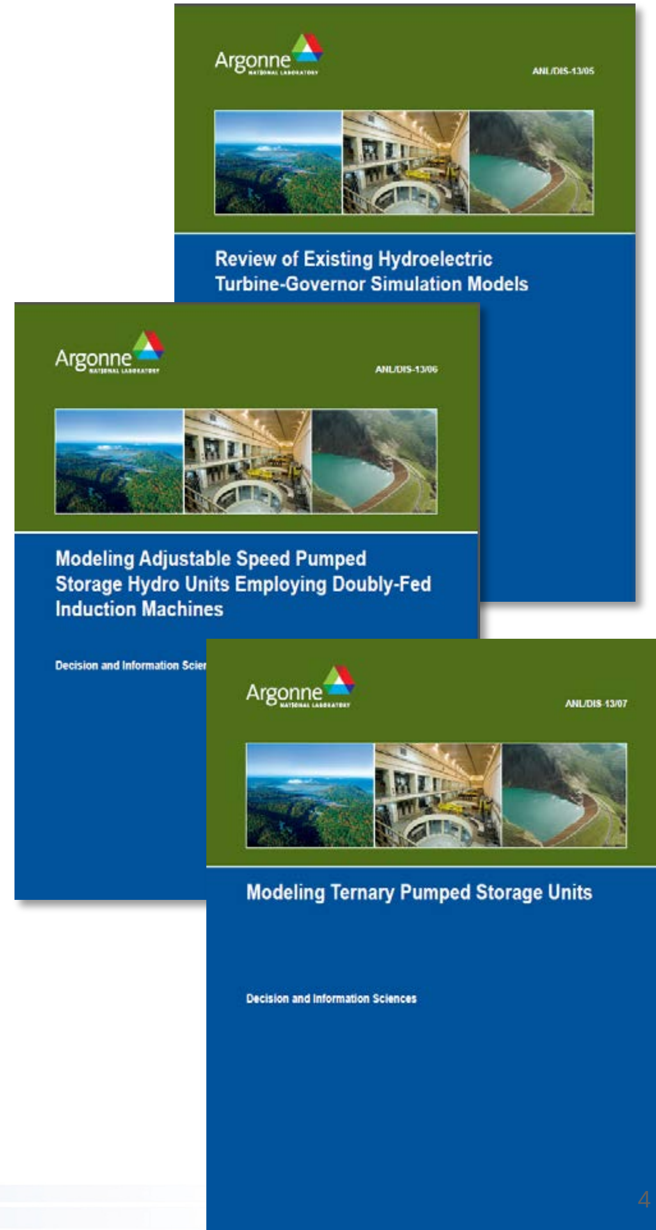
Advanced Technology Modeling – Model Development

Model Development

- Developed vendor-neutral dynamic models for advanced PSH technologies (adjustable speed and ternary units)
  - ✓Review of existing CH and PSH models in use in the United States
  - ✓Dynamic simulation models for adjustable speed PSH
  - ✓Dynamic simulation models for ternary PSH units



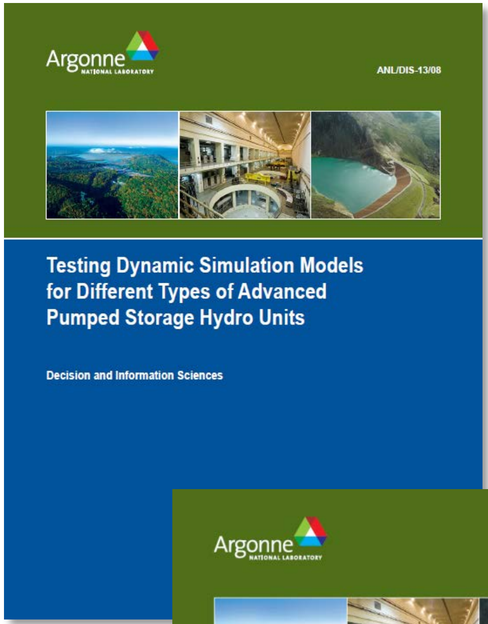
Comparison of system frequency with the FS and AS PSH units in response to generation outage in a test case

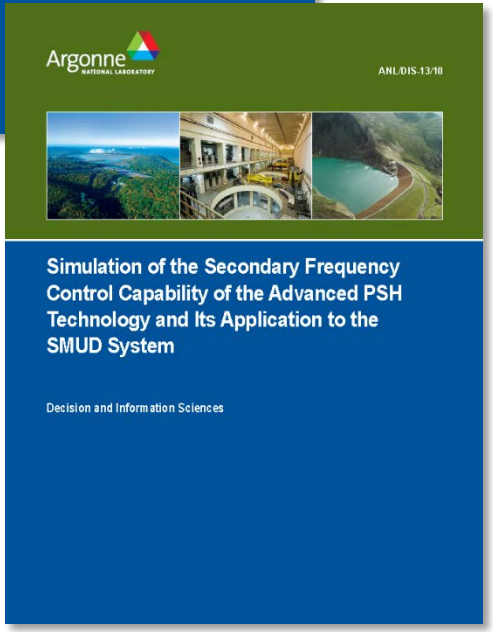


Advanced Technology Modeling – Integration and Testing of Dynamic Models

Model Integration and Testing

- Dynamic models for adjustable speed PSH and ternary units were coded and integrated into the PSS®E model
- Testing of these models for both generating and pumping mode of operation was performed using PSS®E test cases and dynamic cases for Western Interconnection (WI)
- Additional AGC studies have been performed for SMUD balancing authority
- Published a report on frequency regulation capabilities of advanced PSH technologies





Production Cost and Revenue Simulations

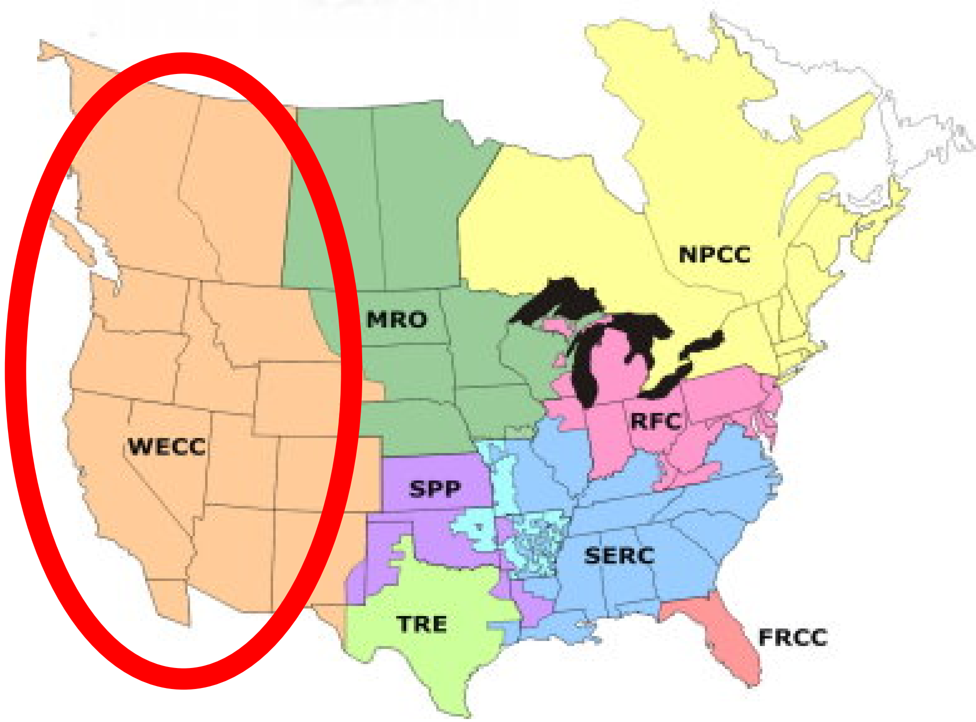
- First, the Project Team developed a matrix of various PSH contributions and services provided to the power system
- A suite of computer models (PLEXOS, FESTIV, and CHEERS) was utilized to simulate system operation and analyze various operational issues occurring at different timescales
- Production cost and revenue simulations were performed to analyze the operation of PSH and the value of their services and contributions to the power system

	PSH Contribution
1	Inertial response
2	Governor response, frequency response, or primary frequency control
3	Frequency regulation, regulation reserve, or secondary frequency control
4	Flexibility reserve
5	Contingency spinning reserve
6	Contingency non-spinning reserve
7	Replacement/Supplemental reserve
8	Load following
9	Load leveling / Energy arbitrage
10	Generating capacity
11	Reduced environmental emissions
12	Integration of variable energy resources (VER)
13	Reduced cycling and ramping of thermal units
14	Other portfolio effects
15	Reduced transmission congestion
16	Transmission deferral
17	Voltage support
18	Improved dynamic stability
19	Black start capability
20	Energy security

PLEXOS Model with Detailed Representation of PSH was Used for Production Cost Simulations

- Several levels of geographical scope, including the entire Western Interconnection, California, and SMUD

- Simulations were conducted for 2022
  - Multiple runs at different time resolutions
  - Hourly simulations for the entire year to determine maintenance schedule of thermal units and annual-level PSH economics
  - Runs at hourly and 5-min time steps for typical weeks in each season to analyze PSH operation under conditions of variability and uncertainty of renewable resources



- Simulations were based on detailed WI grid representation (3,700 generators, 17,000 transmission buses) and examined impact of different levels of wind and solar penetration

Production Cost and Revenue Simulations with PLEXOS

Cost-based approach was applied for WI and SMUD, while market-based approach was applied for California simulations

Two sets of PLEXOS runs for each simulated system:

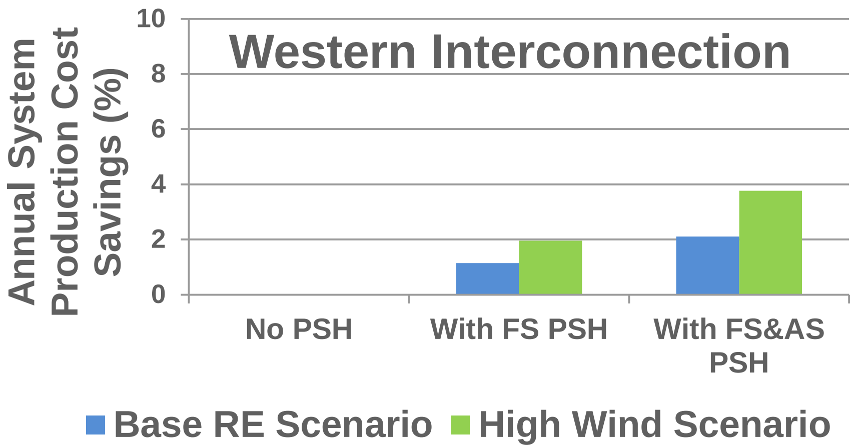
- ***Annual runs*** for Base and High Wind RE scenarios (DA runs with hourly time step and co-optimization of energy and ancillary services):
  - Without PSH plants
  - With existing conventional (fixed-speed) PSH plants
  - With existing FS PSH and proposed new adjustable speed PSH

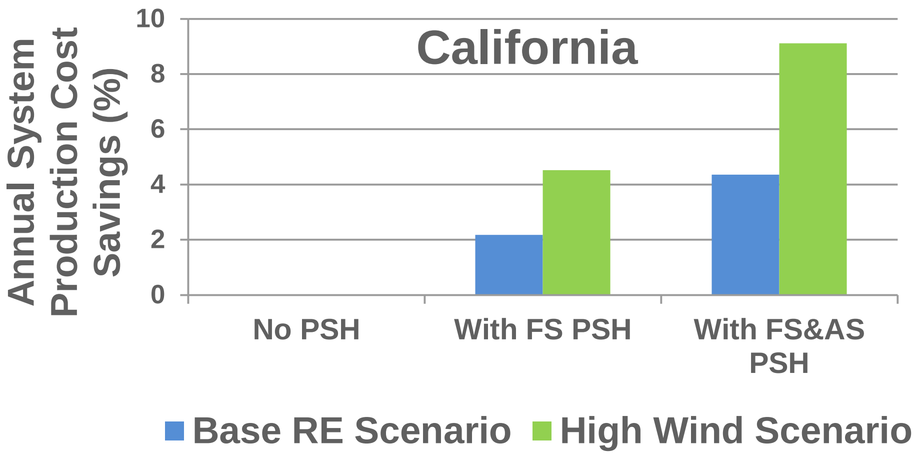
- ***Weekly runs*** for four typical weeks in different seasons (January, April, July, and October) applying three-stage approach (DA-HA-RT with 5-min time step) and co-optimization of energy and ancillary services:
  - Without PSH plants
  - With existing FS PSH plants
  - With existing FS PSH and proposed adjustable speed PSH

Annual Simulation Results Show that PSH Significantly Reduces Power System Operating Costs

Production Cost Savings due to PSH Capacity in 2022

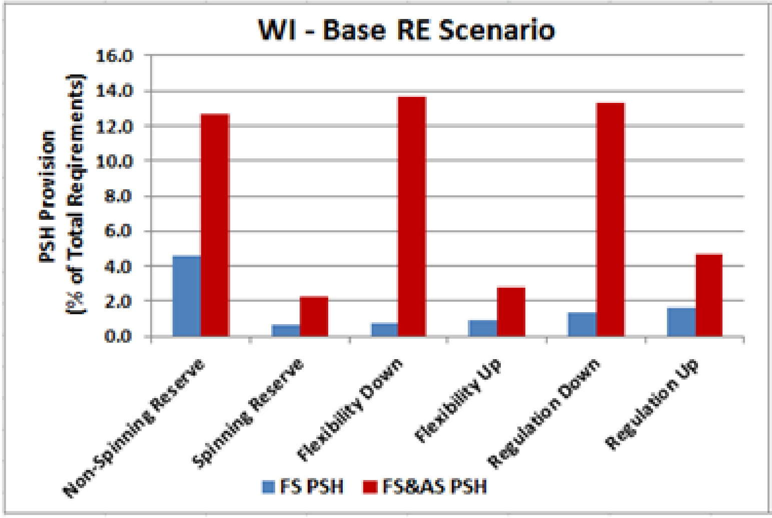
Annual Production Cost Savings due to PSH Capacity ($ Million)	Western Interconnection		California		SMUD	
	Base Renewable Scenario	High Wind Renewable Scenario	Base Renewable Scenario	High Wind Renewable Scenario	Base Renewable Scenario	High Wind Renewable Scenario
With FS PSH	167	248	111	186	-	-
With FS & AS PSH	311	477	171	376	23	51

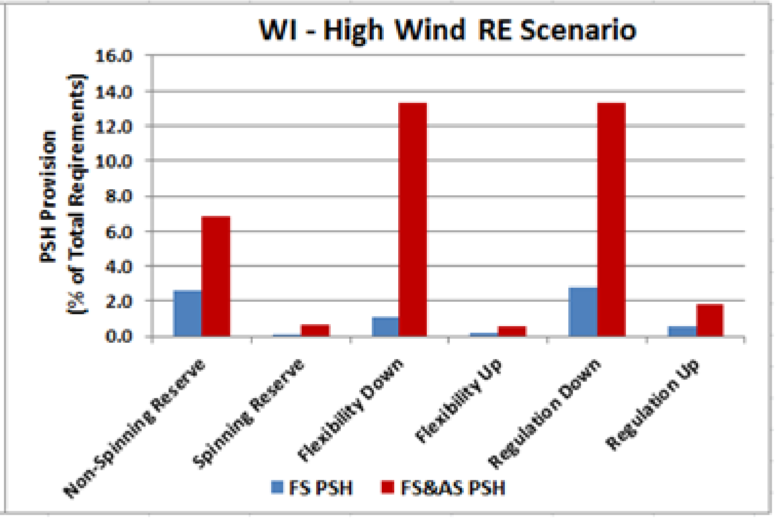




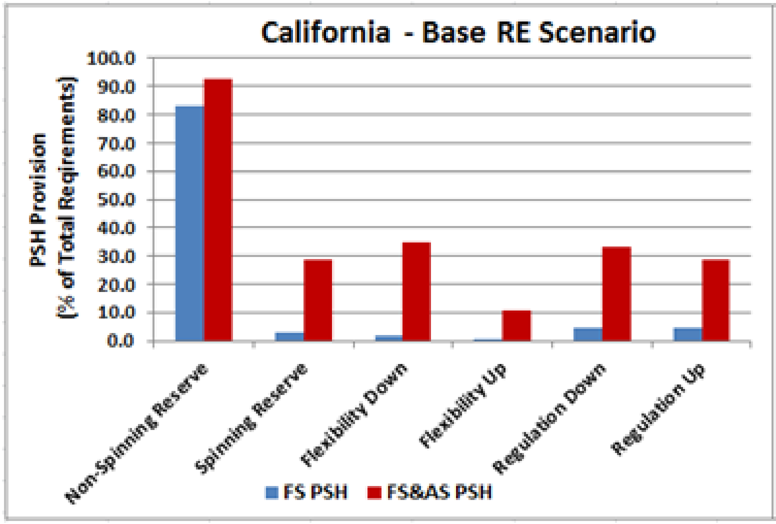
PSH Provisions of System Reserves in 2022 (As % of Total System Requirements)

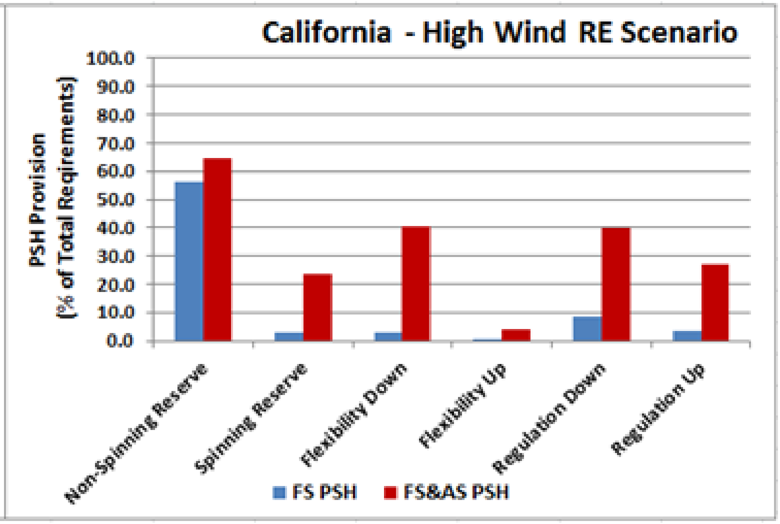
- Western Interconnect



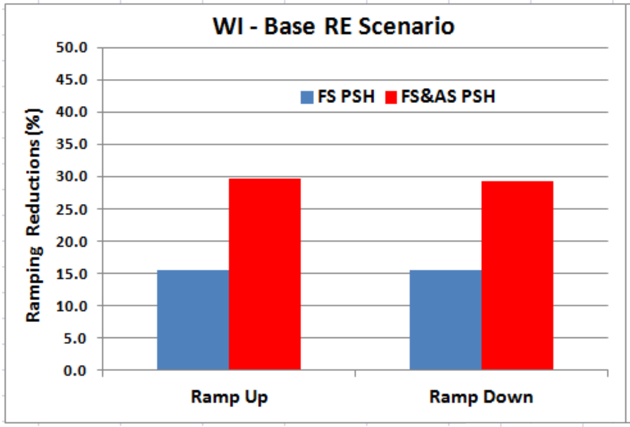


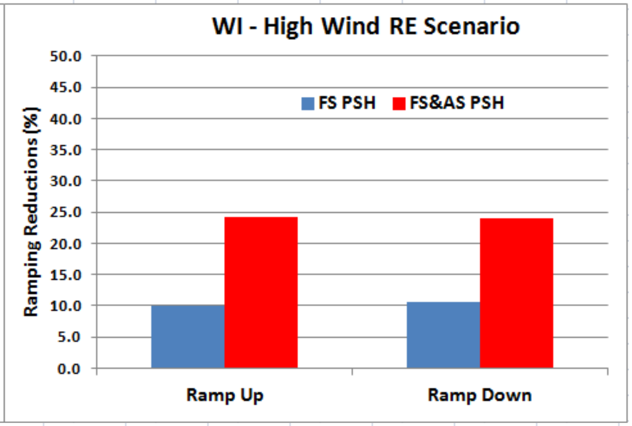
- California:

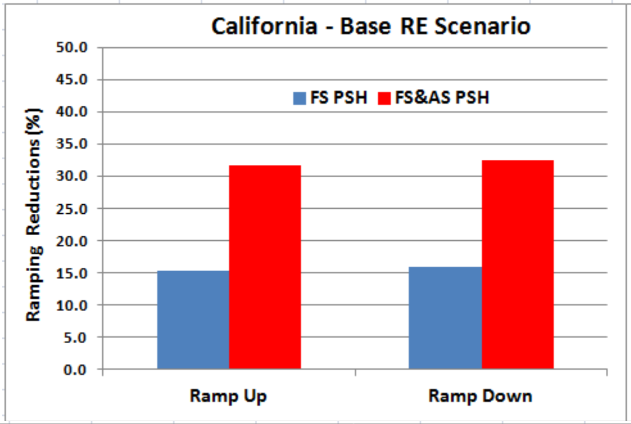


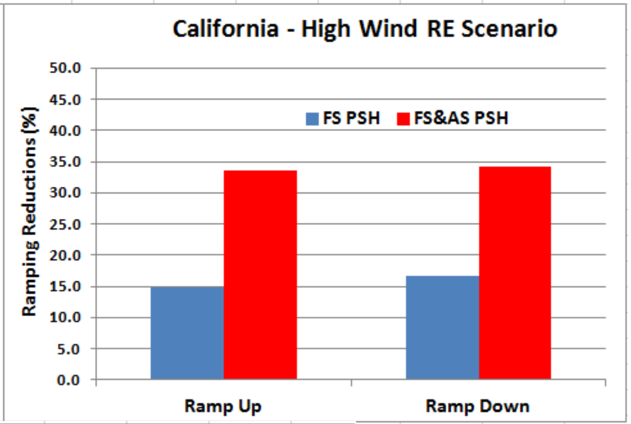


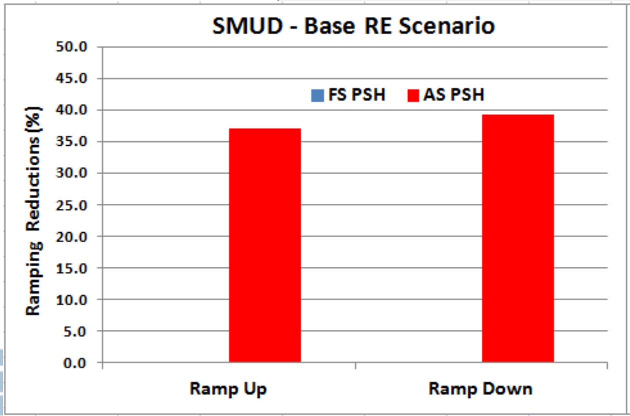
Reductions in Thermal Generator Ramping in 2022 due to PSH Capacity

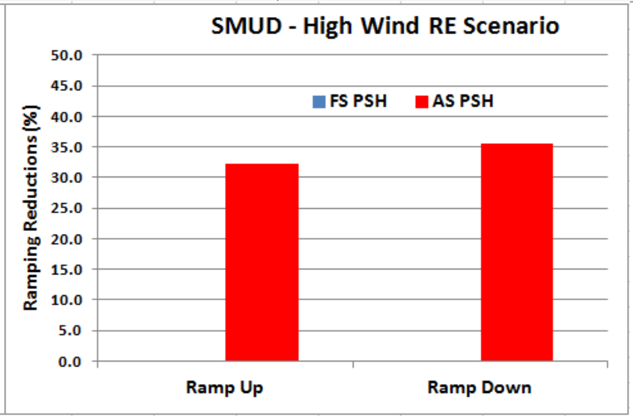












California: Thermal Generator Cycling in 2022

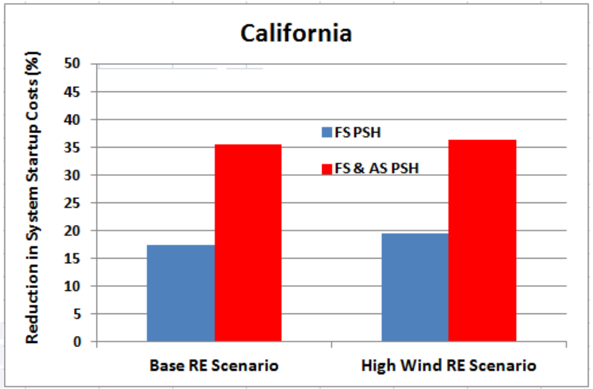
- Baseline RE scenario:

Base Renewable Scenario	Total Number of Thermal Starts	Total Thermal Start Cost	Cost Reduction	
		$ Million	$ Million	%
No PSH	18,514	56	-	-
With FS PSH	14,646	46	10	17.35%
With FS&AS PSH	12,134	36	20	35.40%

- High Wind RE scenario:

High-Wind Renewable Scenario	Total Number of Thermal Starts	Total Thermal Start Cost	Cost Reduction	
		$ Million	$ Million	%
No PSH	17,862	54	-	-
With FS PSH	14,351	44	11	19.56%
With FS&AS PSH	11,864	35	20	36.42%

FS & AS PSH plants reduce cycling cost of thermal units by one third



Western Interconnection: Impact of PSH on RE Curtailments in 2022

- Baseline RE scenario:

Base RE Scenario	Curtailed Energy	Renewable Curtailment Reduction	
	GWh	GWh	%
No PSH	1,921	-	0%
With FS PSH	1,356	565	29%
With FS&AS PSH	964	958	50%

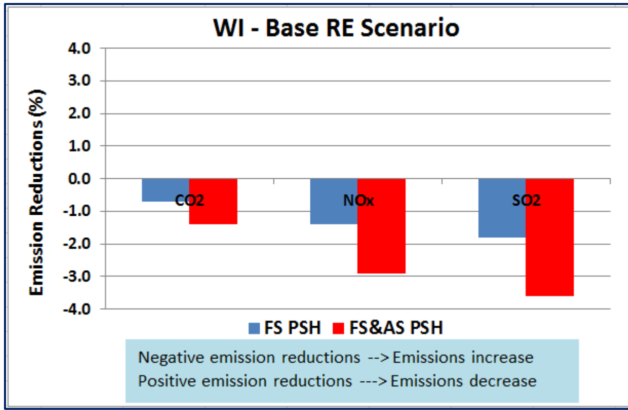
RE curtailments reduced 50%

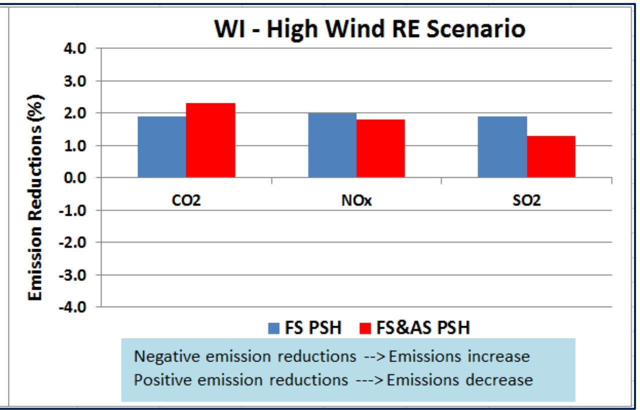
- High Wind RE scenario:

High Wind RE Scenario	Curtailed Energy	Renewable Curtailment Reduction	
	GWh	GWh	%
No PSH	56,885	-	0%
With FS PSH	48,403	8,482	15%
With FS&AS PSH	44,211	12,675	22%

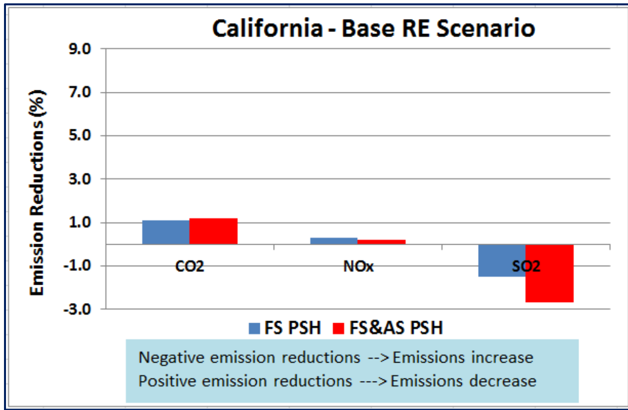
Annual generation of about 5,000 MW of wind capacity

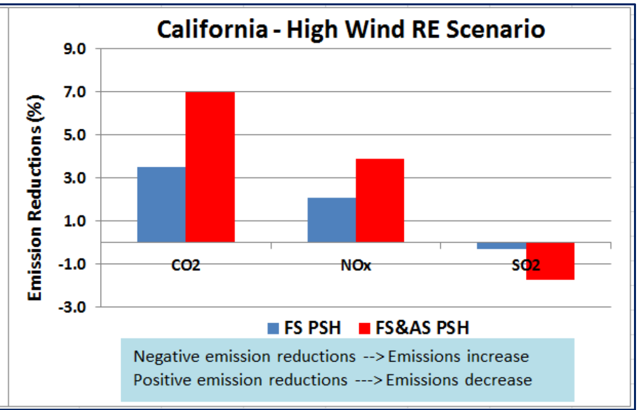
PSH Impacts on Power System Emissions



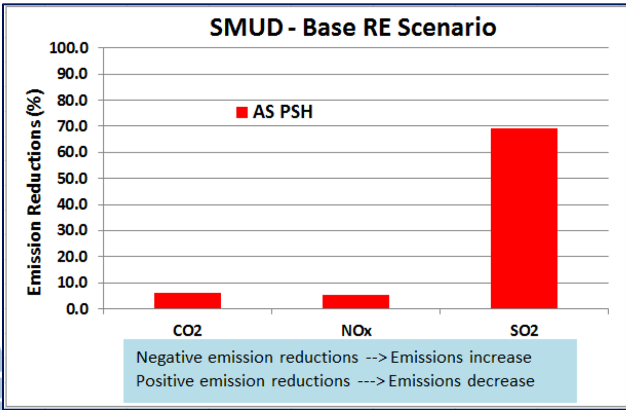


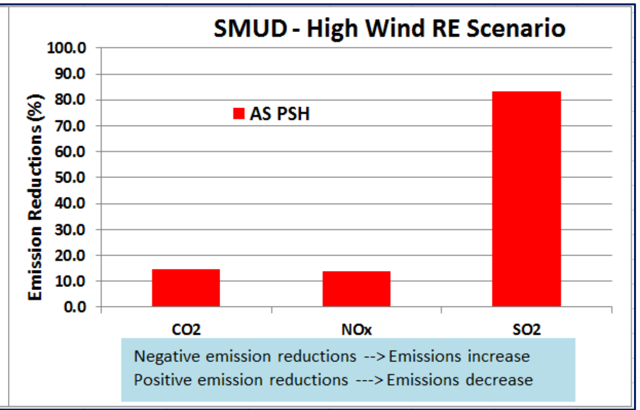
WI: Emissions increase under Base RE scenario, but decrease under High Wind RE scenario





California: CO2 and NOx emissions decrease, SO2 emissions increase under both scenarios

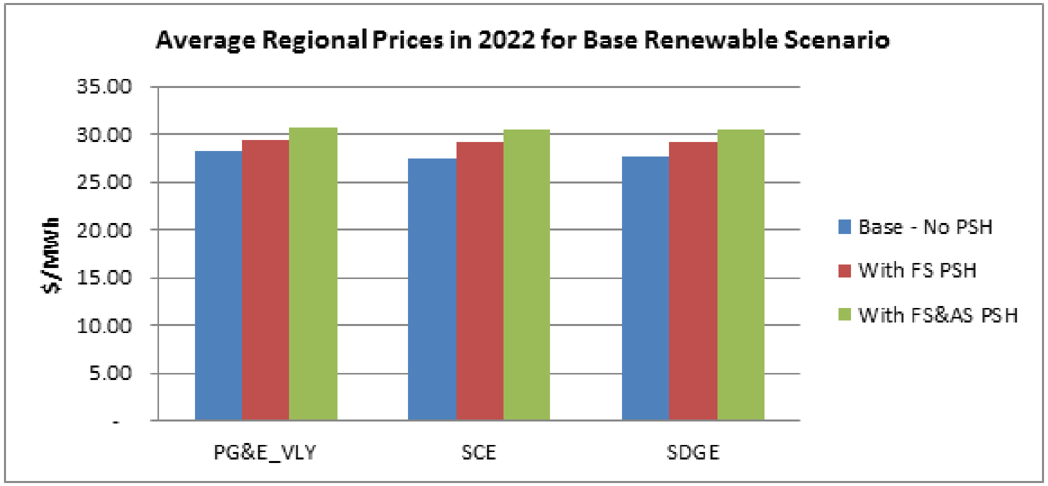




SMUD: Emissions decrease under both scenarios

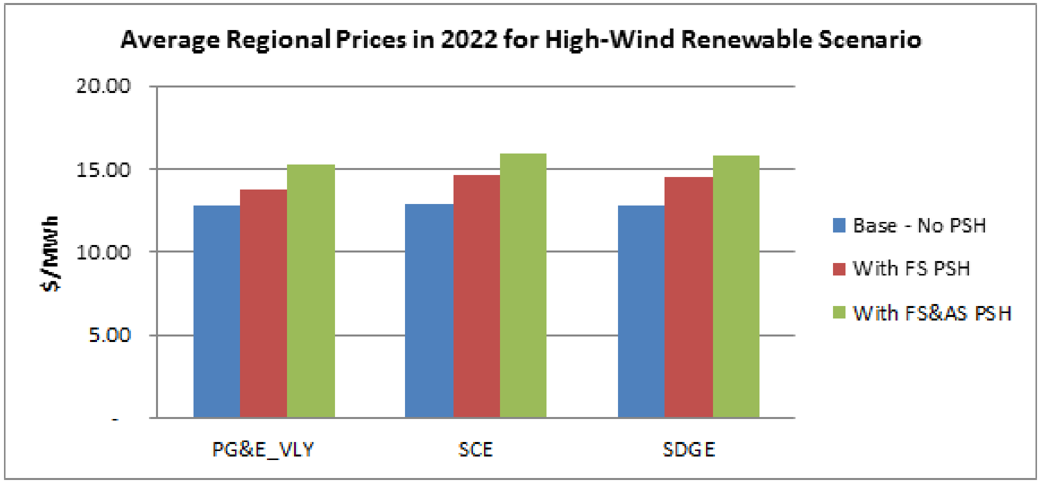
California: Regional LMPs in 2022 Are Significantly Lower under High-Wind RE Scenario

- Baseline RE scenario:



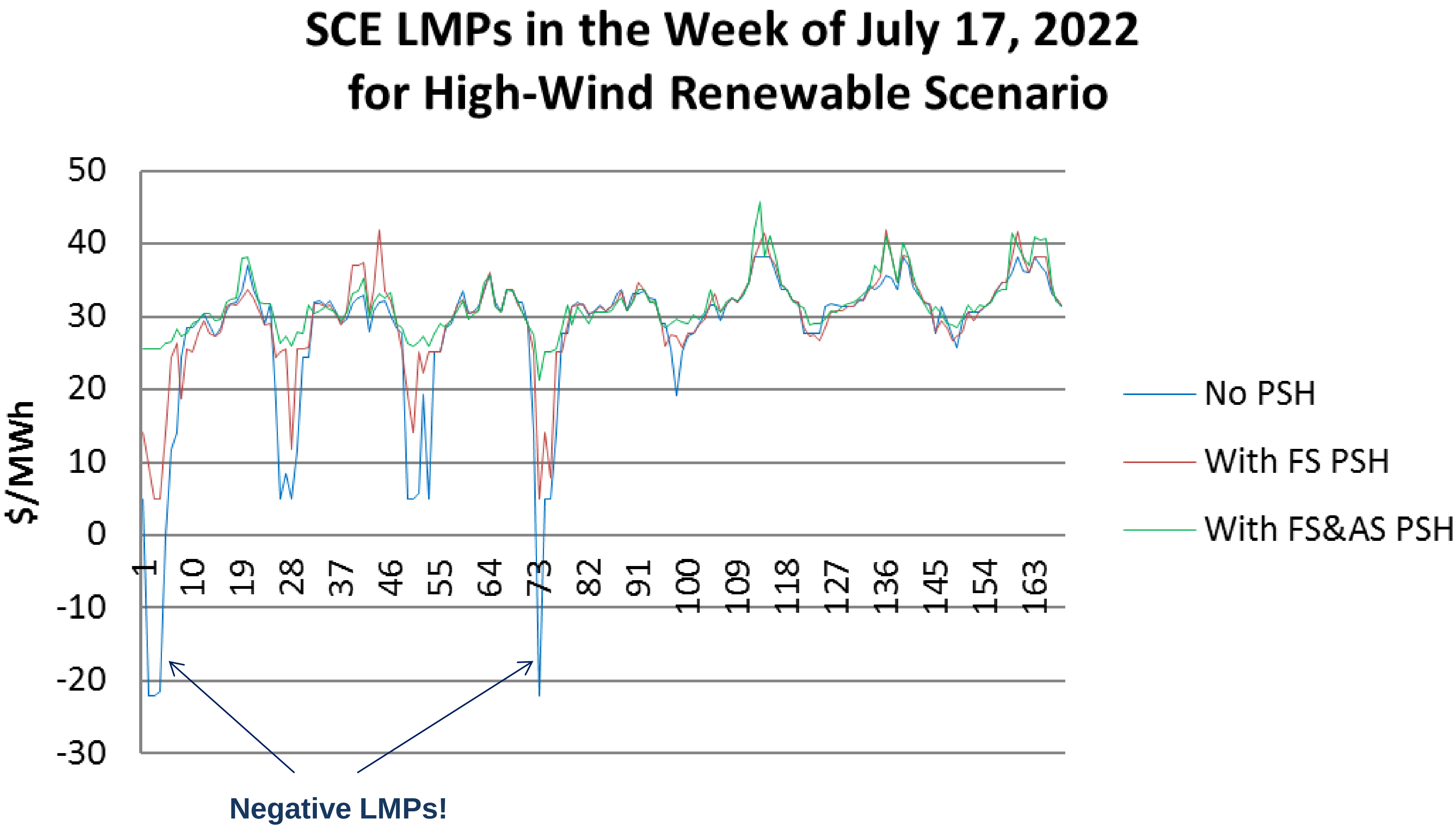
Average LMPs: 27-30 $/MWh

- High-Wind RE scenario:



Average LMPs: 13-16 $/MWh

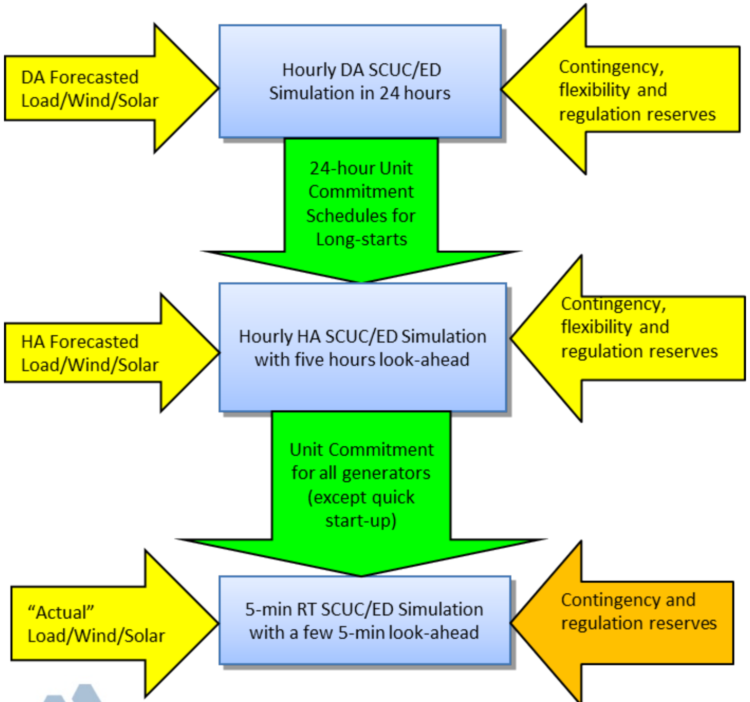
PSH Provides Load for RE Generation during Off-Peak Hours (Reduces RE Curtailments and Negative LMPs)



3-Stage DA-HA-RT Modeling

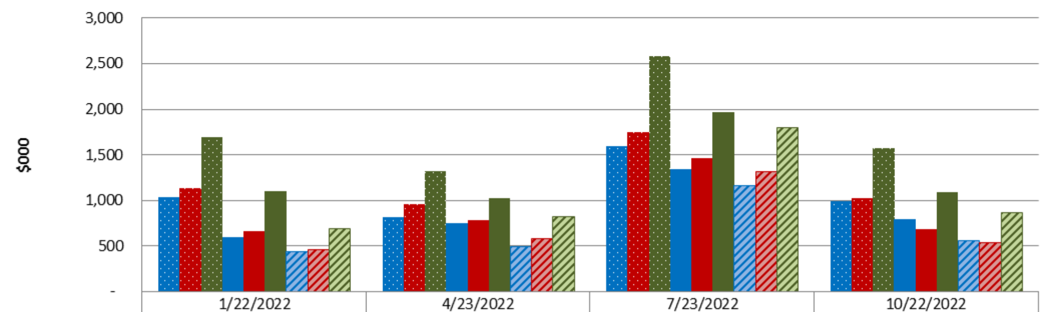
- Detailed simulation (5-minute time step in RT simulations) of four typical weeks in different seasons of 2022 under High-Wind RE scenario
- Simulated: 3rd weeks of January, April, July, and October
- 3rd week in July is the peak load week

3-Stage Sequential Simulation



Results for Startup and Shutdown Costs in California under High-Wind Scenario

California Start & Shutdown Cost ($000) from 3-Stage Simulations for Three Cases and Four Typical Weeks in Year 2022 in High Wind Renewable Scenario (Maintenance & Forced Outages in the RT Simulations)



	1/22/2022	4/23/2022	7/23/2022	10/22/2022
No PSH DA	1,032	821	1,595	990
No PSH HA	1,138	954	1,750	1,024
No PSH RT	1,690	1,320	2,580	1,575
FS PSH DA	595	753	1,344	799
FS PSH HA	667	781	1,468	686
FS PSH RT	1,104	1,027	1,973	1,085
FS&AS PSH DA	439	489	1,157	559
FS&AS PSH HA	464	578	1,313	541
FS&AS PSH RT	695	819	1,796	870

Summary of 3-Stage DA-HA-RT Modeling Results

Summary of 5-minute RT simulation results for High-Wind renewable generation scenario

High Wind Renewable Scenario	Average Cost Savings or Decrease in Ramping Needs due to PSH Capacity over the Four Simulated Typical Weeks in 2022			
	System Production Costs Savings	Startup and Shutdown Costs Savings	Ramp Up of Thermal Generators	Ramp Down of Thermal Generators
	%	%	%	%
Western Interconnection				
With FS PSH	2.01	11.21	5.44	8.25
With FS & AS PSH	3.60	17.71	23.25	24.86
California				
With FS PSH	5.01	27.58	9.76	15.10
With FS & AS PSH	7.27	41.67	33.05	64.16
SMUD				
With AS PSH	14.31	10.62	22.06	22.87


Questions?
THANK YOU!