Value and Role of Pumped Storage Hydropower under High Variable Renewables

Chrissy Bisceglia
Senior Engineer
GE Energy Consulting

VALUATION OBJECTIVES

EVALUATE AND UNLOCK FULL POTENTIAL OF PSH TO SUPPORT GRID OPERATIONS, STABILITY & RESILIENCY

Overcome market barriers and enable PSH technology deployment for utilities, Public Utility Commissions (PUCs), developers and regional planners

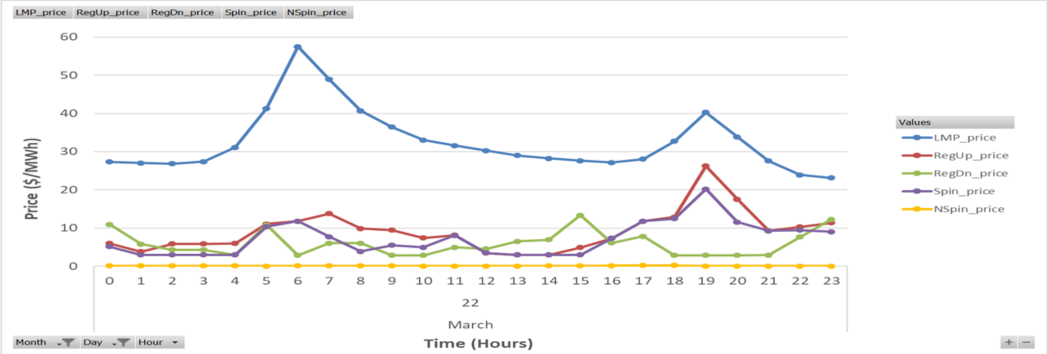
- Develop a **PSH scheduling tool** to co-optimize energy and ancillary services, considering price elasticity in the power market
- Analyze and quantify the **potential value of PSH** under different system conditions
- Develop a set of **Variable Speed PSH stability models** for transmission planners to study the impact of PSH on the grid
- Investigate the dynamic **stability capability of VSPSH** and assess its impact on grid frequency response and transient stability
- Investigate the **PSH contribution to resource adequacy**

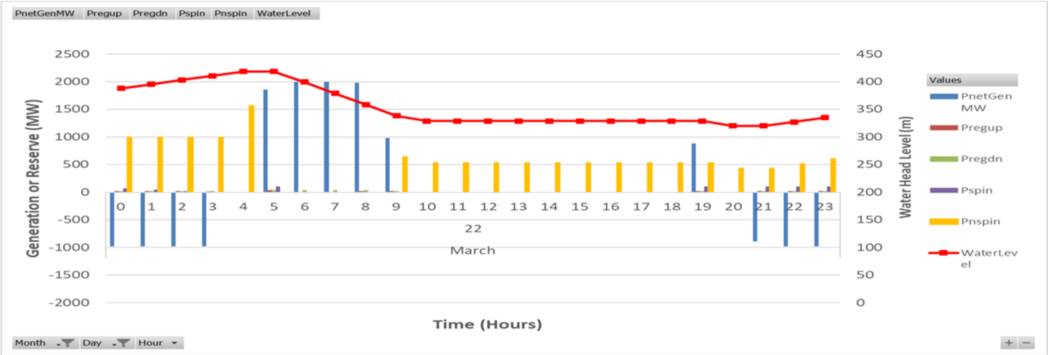
PSH SCHEDULING TOOL

Goals: Maximize PSH operating profit on a given optimization horizon while respecting operational and scheduling constraints and enabling PSH developers and owners to unlock PSH value from both ancillary services and energy.

- A novel PSH Scheduling tool was developed, incorporating for the first time the impact of variable height differences between reservoirs ('head') and variable speed machine behavior.
- The tool is run in conjunction with a production cost optimization tool to allow for price elasticity effects to be captured.
- Developed in Python open source software and can be easily modified to meet future needs.

CAISO Market Prices for March 22, 2018

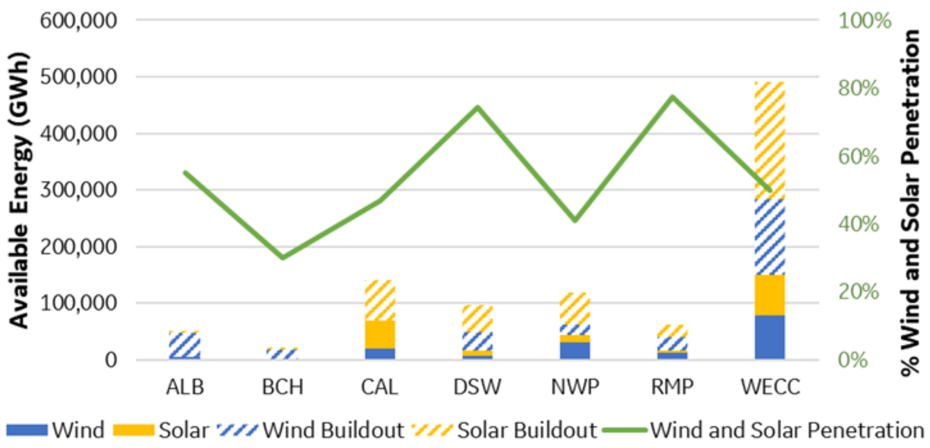


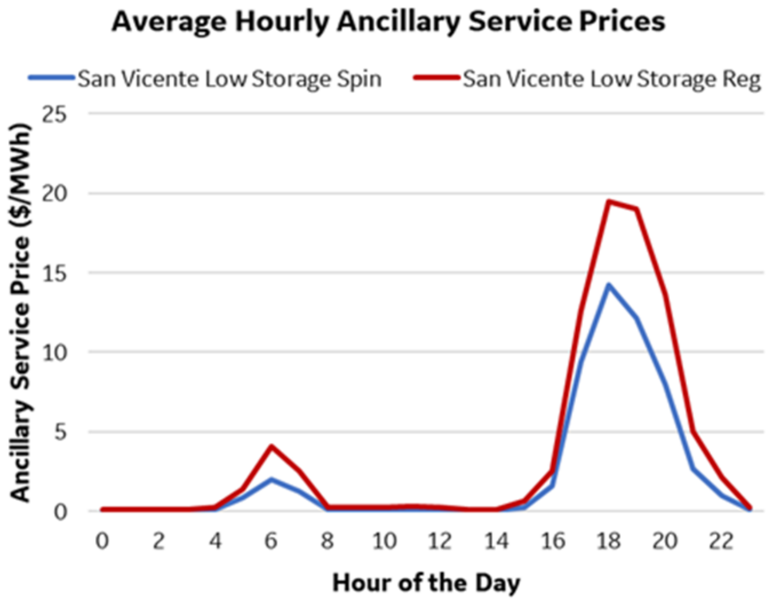


PSH optimal dispatch

PRODUCTION COST MODELING: Base Assumptions

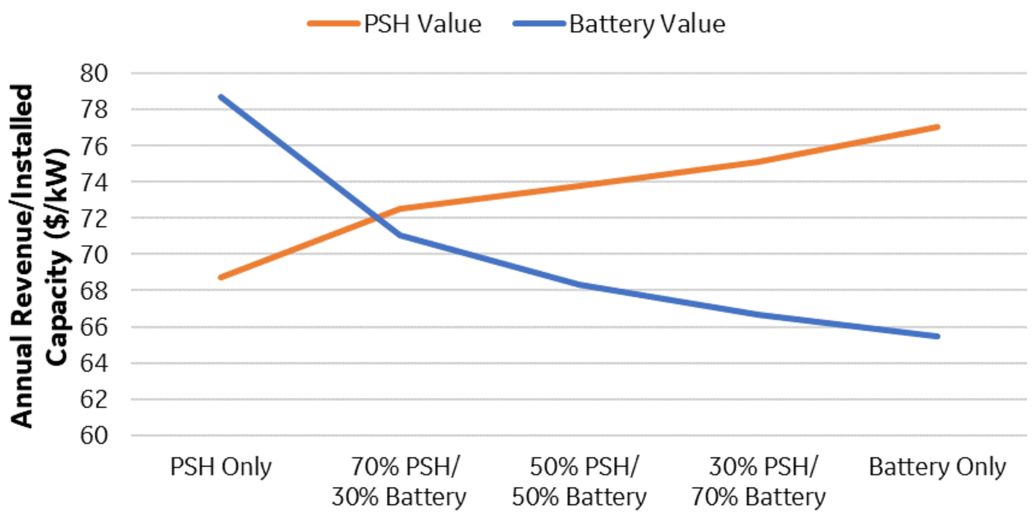
- GE non-proprietary WECC database 2028 study year with 50% renewable penetration
- Economic retirement analysis performed after the renewable additions.
- Simple transmission expansion exercise to alleviate congestion due to generic renewable buildout.
- The base case, referred to as "low storage", includes some PSH and battery storage (8 TWh of PSH, 3 TWh of battery)
- Ancillary service modeling:
  - CAISO 2017-2018 IRP production cost model requirements for regulation and spinning reserve
  - GE MAPS calculates hourly total ancillary service price
  - Historical CAISO prices used to determine how much of the total price for each ancillary product

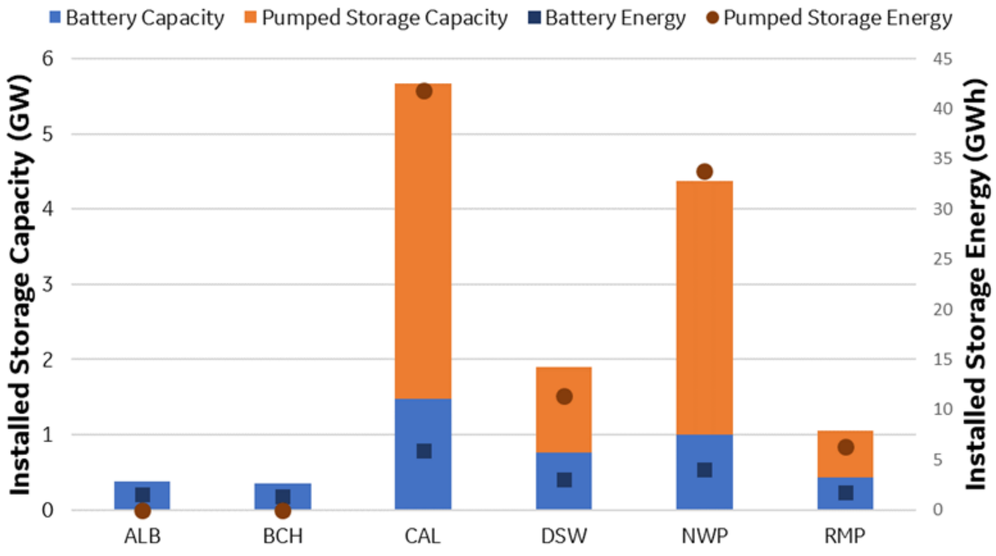




PRODUCTION COST MODELING: High Storage Scenario

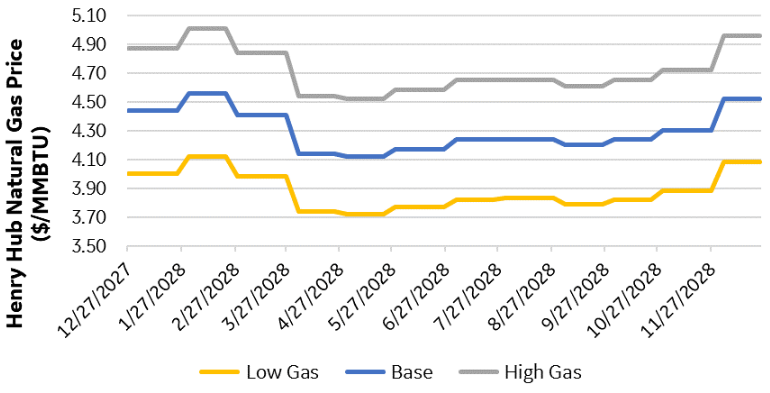
- High Storage scenario developed to understand the value of PSH with more storage competition.
- A storage value metric (Annual Revenue $/Installed Capacity kW) was used to determine when the system begins to be saturated (a 25% decrease was chosen as the "saturation point" for this study)
- When PSH or Battery technologies were added alone, the value metric decreased by 25% when approximately 14 GW were installed.
- Various mixes of PSH and Battery technology were calculated and a 70% PSH (9.8GW, 98GWh) and 30% Battery (4.2 GW, 16.8 GWh) scenario was selected



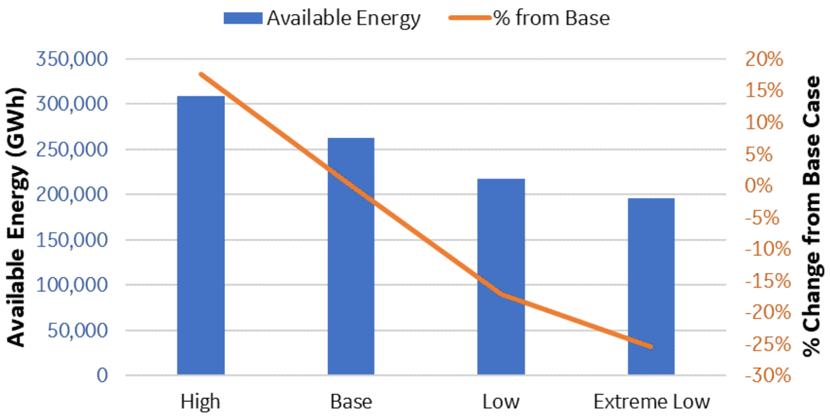


PRODUCTION COST MODELING: Cases & Outputs

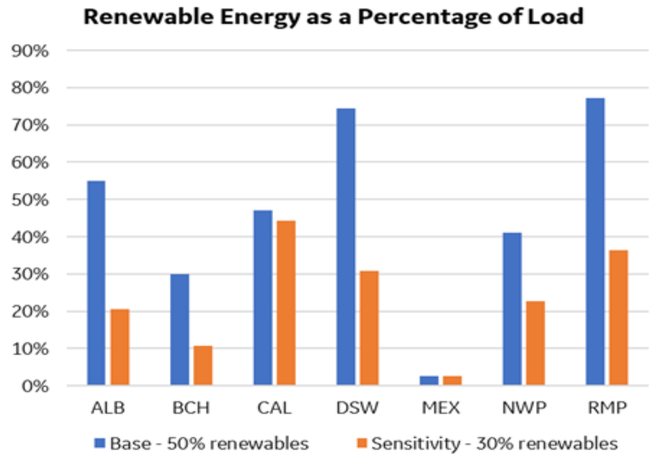
Natural Gas Sensitivities



Hydro Sensitivities



30% Renewable Penetration

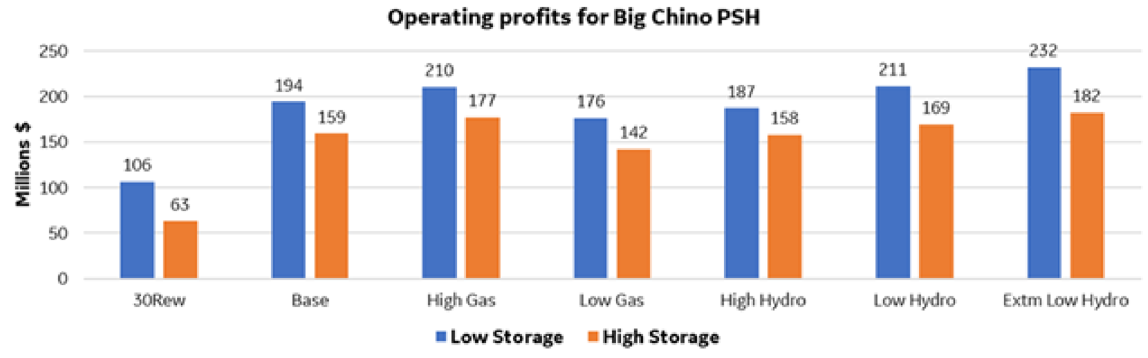


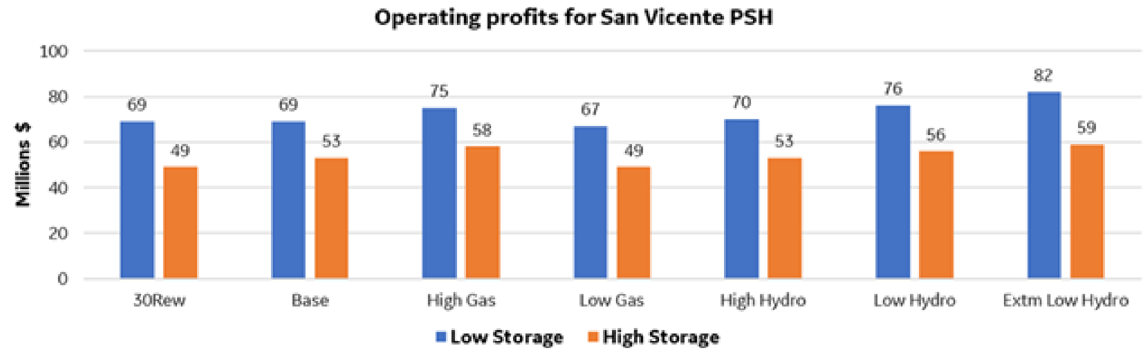
- Total of 42 cases, low and high storage scenarios with base case and 6 sensitivities
- The PSH plant schedules were revenue-optimized using the scheduling tool developed by GE Global Research.
- Results analyzed for both WECC-wide system impact and individual plant revenue

	Big Chino	San Vicente
Capacity (MW)	2,000	500
Duration(hrs)/ Energy (MWh)	10/20,000	8/4,000
Location	AZ	CA
Revenue Streams	Energy	Energy & Ancillary Services

PRODUCTION COST MODELING: Results

Delta From Case without Units	Production Cost ($/M)		CO2 Emissions (million tons)		Simple Cycle Peaker Cycling		Curtailment (GWh)	
	W/ Big Chino	W/ San Vicente	W/ Big Chino	W/ San Vicente	W/ Big Chino	W/ San Vicente	W/ Big Chino	W/ San Vicente
Base Low Storage	-182	-62	-1.82	-0.5	-4,762	-1,572	-4,753	-1,102
30% Renewables Low Storage	-93	-46	-0.15	-0.24	-5,936	-2,137	-1,406	-550
High Gas Price Low Storage	-194	-61	-1.72	-0.46	-4,587	-1,337	-4,790	-1,102
Low Gas Price Low Storage	-164	-56	-1.73	-0.43	-4,752	-1,625	-4,666	-1,114
High Hydro Low Storage	-184	-56	-1.68	-0.41	-5,676	-1,860	-4,811	-1,115
Low Hydro Low Storage	-195	-62	-1.62	-0.45	-5,387	-2,429	-4,399	-1,028
Extreme Low Hydro Low Storage	-202	-64	-1.55	-0.42	-4,820	-2,182	-4,324	-1,032
Base High Storage	-167	-48	-1.65	-0.39	-4,461	-2,132	-4,189	-806
30% Renewables High Storage	-58	-28	0.02	-0.07	-3,664	-2,637	-737	-278
High Gas Price High Storage	-181	-51	-1.74	-0.44	-4,707	-1,660	-4,312	-845
Low Gas Price High Storage	-143	-34	-1.74	-0.27	-3,023	-371	-4,274	-733
High Hydro High Storage	-165	-36	-1.71	-0.33	-5,073	-1,851	-4,412	-834
Low Hydro High Storage	-181	-48	-1.76	-0.29	-5,793	-1,700	-4,038	-772
Extreme Low Hydro High Storage	-184	-50	-1.7	-0.39	-5,302	-2,143	-4,118	-863





Positive system impact in all scenarios, no clear winner.

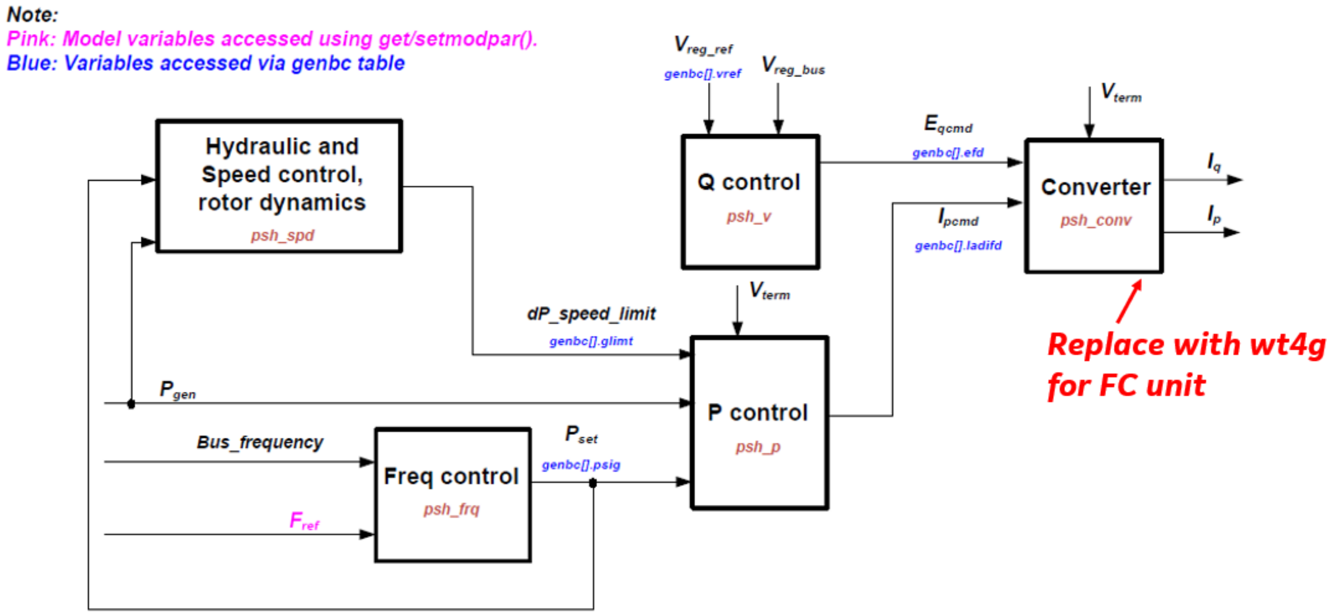
- Up to $202M/$64M reduction in Production Cost
- Up to 1.82/0.5 million tons of CO2 reduction
- Significant reduction in peak cycling and curtailment reduction

PSH plant revenue:

- Highest revenue in high renewable and high gas scenarios
- Reduced by more competing storage and lower renewables

DYNAMIC MODELING: PSLF Models & Benchmarking

- Suite of models added to PSLF to represent variable speed pumped hydro storage units largely based on the models developed as part of a previous DoE project* with minor updates based on GE Hydro's Powerfactory model.
- Benchmarking done against previous DoE project's PSSE model and GE Hydro's Powerfactory model for small test cases
- Reference tests included:
  - Voltage
  - Frequency response
  - Active power
  - Generator loss events
  - Fault response



- Frequency and Fault response of models was ensured to be reasonable for a high renewable WECC case as well.

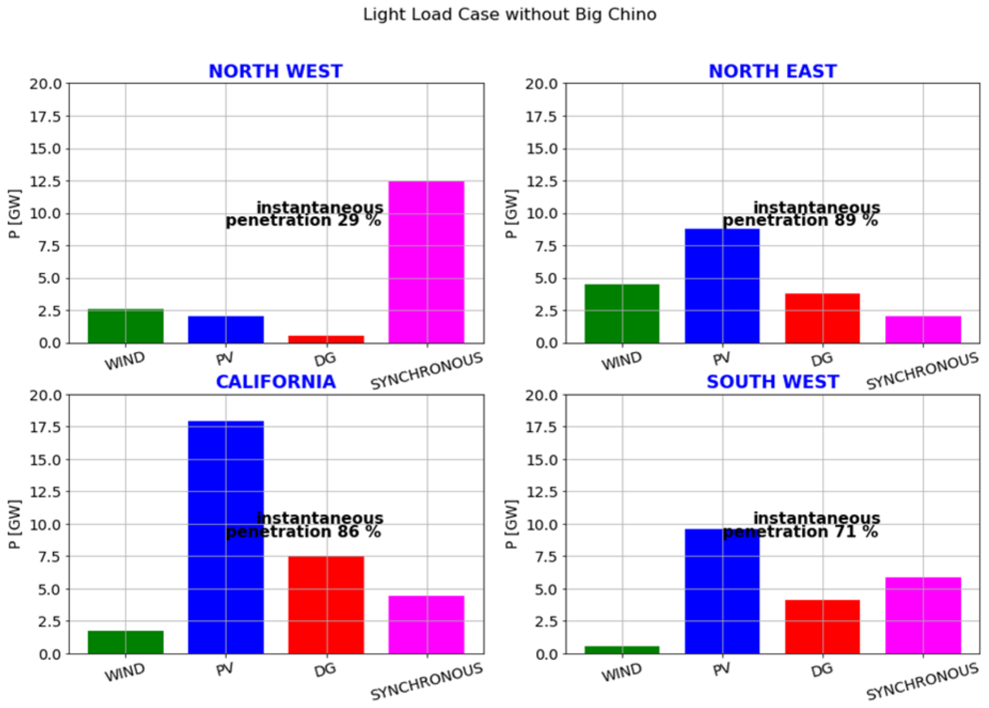
* https://ceeesa.es.anl.gov/projects/psh/psh.html

DYNAMIC MODELING: Assessment at Big Chino Set-Up

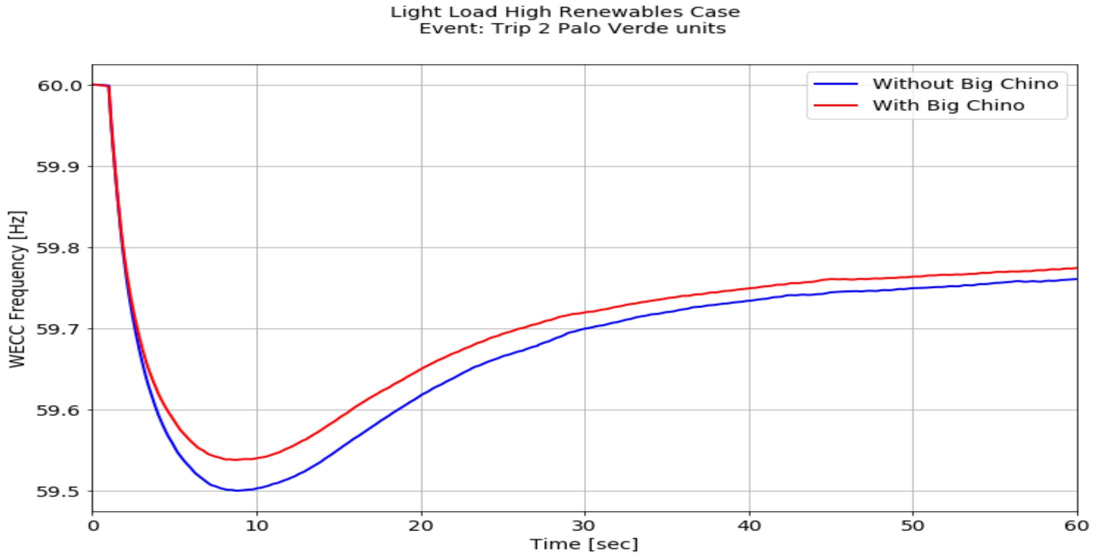
- All hours of the year from GE MAPS model filtered to select pinch points in frequency response capability
- The 2022 light load spring case load and generation were scaled to meet the average of these hours
  - MW outputs of generators scaled to meet MAPS area/unit type targets.
  - Loads scaled to meet the MAPS area loads

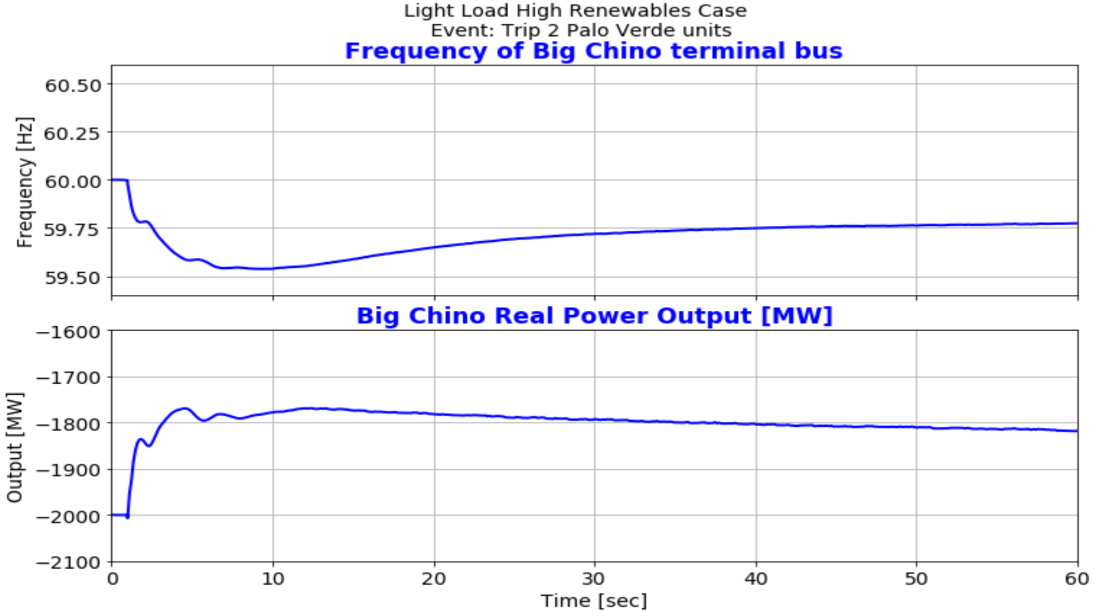
GE MAPS Model Frequency Pinch Point Criteria

- Spring
- between 10am and 3pm
- PSH Is pumping greater than 3000 MWh
- Wind + Solar generation > exceeds 60,000 MWh
- load is between 95,000 and 105,000 MWh
- Wind + Solar generation is 73% of load or more



DYNAMIC MODELING: Assessment at Big Chino Results





Frequency response margin and RoCoF without Big Chino

Area	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	ROCOF (between 1 and 1.125s) [Hz/s]
WECC	858	**739.73**	**-118.27**	0.31
CALIFORNIA	261.53	42.22	-219.31	0.44
DESERT SOUTHWEST	146.04	**67.17**	**-78.87**	0.93
NORTHEAST	149.85	21.22	-128.63	0.27
NORTHWEST	146.81	347.82	201.015	0.08

Frequency response margin and RoCoF with Big Chino

Area	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	ROCOF (between 1 and 1.125s) [Hz/s]
WECC	858	**814.18**	**-43.82**	0.31
CALIFORNIA	261.53	42.21	-219.32	0.43
DESERT SOUTHWEST	146.04	**145.50**	**-0.54**	0.91
NORTHEAST	149.85	20.46	-129.39	0.26
NORTHWEST	146.81	346.33	199.52	0.08

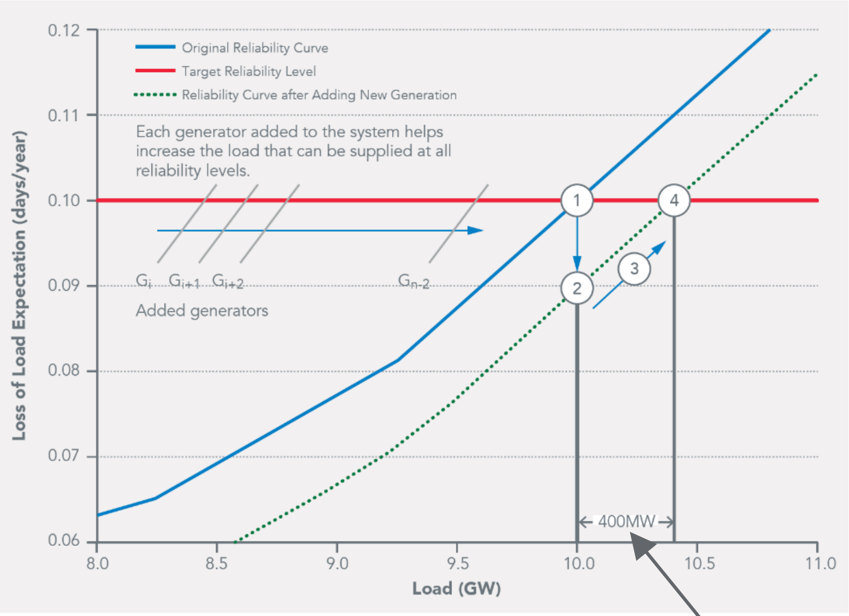
DYNAMIC MODELING: Additional Results

- Critical Interfaces: Big Chino plant has no measurable impact. Critical outages for these interfaces have no significant impact and the system is stable post-disturbance.
- Fault Response: For a nearby severe three-phase fault, the Big Chino plant:
  - Responds to arrest the voltage decline by increasing its reactive power output and reducing its pumping load.
  - The terminal voltage in the case with Big Chino is higher than in the case without it having a slight positive impact on the system.
  - FSPSH gives greater reactive power contribution during the fault which is good, however once the fault is cleared its output oscillates for longer before settling. VSPSH settles after fault clearance much more quickly.

A Variable Speed PSH unit has a positive impact on grid frequency response and transient stability

CAPACITY VALUE: Approach

- Calculate capacity value of storage, for different ratios of energy/capacity (hours of storage)
- Simulations in GE MARS with same basic assumptions and PSH plants as production cost model
- Impact of wind/solar presence in the system to the capacity value
- Developed new GE MARS version which supports dynamic dispatch of storage
- Loss-of-load expectation (LOLE)-based analysis determined the effective load carrying capability (ELCC) of the incremental storage
- Capacity value is the resource’s contribution towards meeting a reliability target.



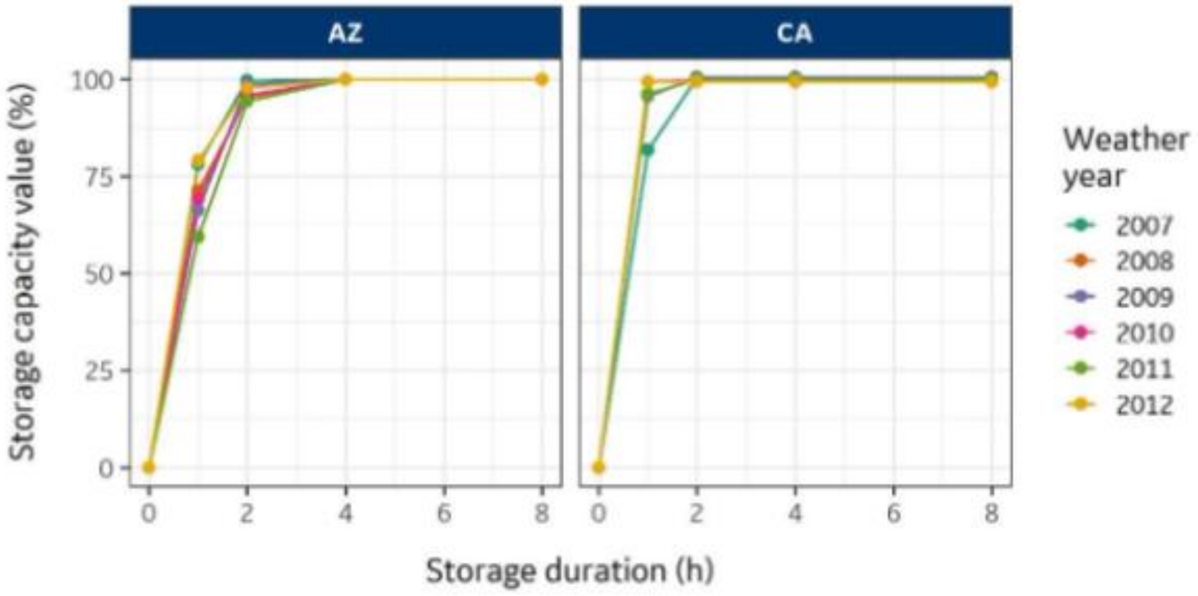
1. Initial system
2. Add resource, reliability improves
3. Increase load
4. Match initial reliability target

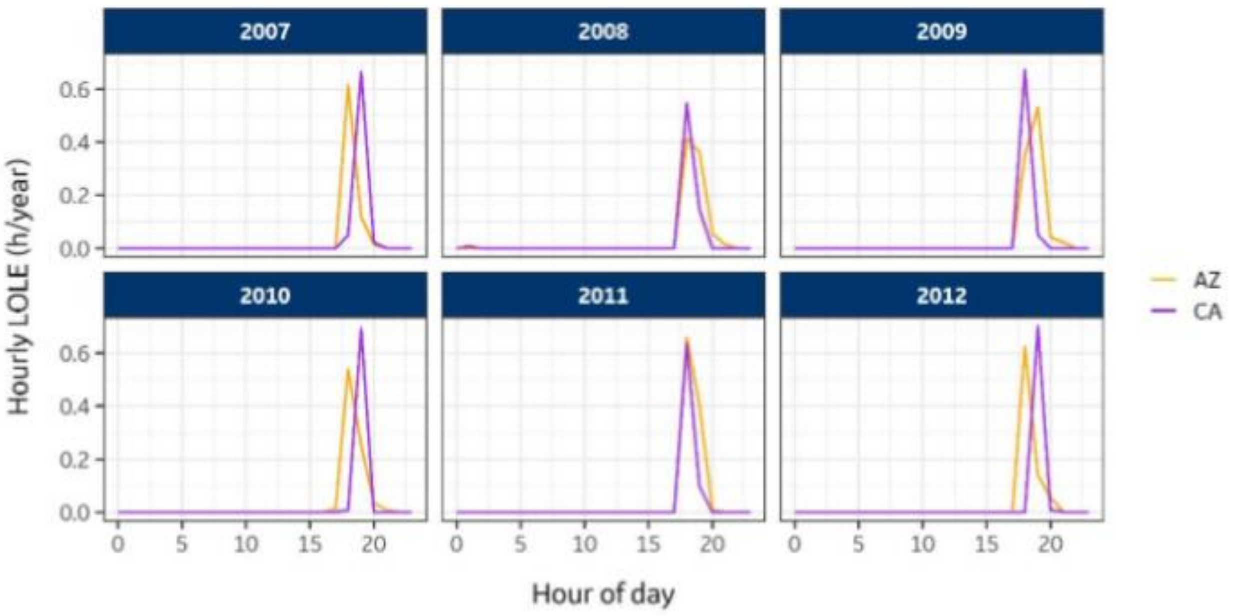
Capacity value

J. Katz, P. Denholm “Using Wind and Solar to Reliably Meet Electricity Demand, Greening the Grid” http://www.nrel.gov/docs/fy15osti/63038.pdf

CAPACITY VALUE: Base Case Results

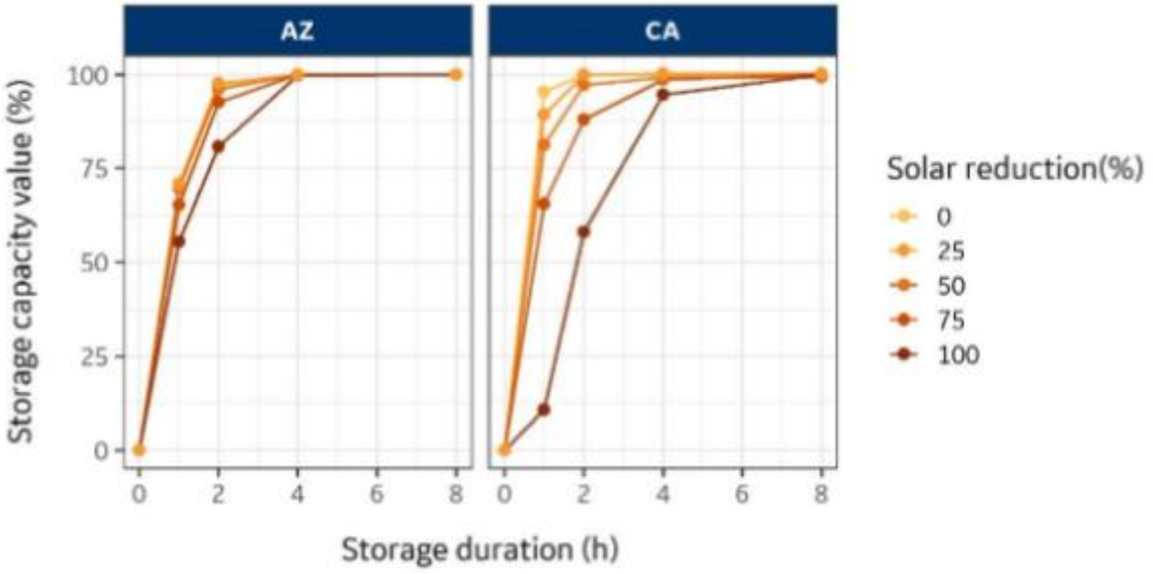
- Each ELCC calculation was done for 6 years of wind, solar, and load shapes (2007-2012), results are similar
- Results show Capacity Value as a % of nameplate capacity
- Base case results are above 95% with 2 hours of storage in AZ and with 1 hour of storage in CA
- High renewable penetration caused LOLE to be for periods of ~1 hour

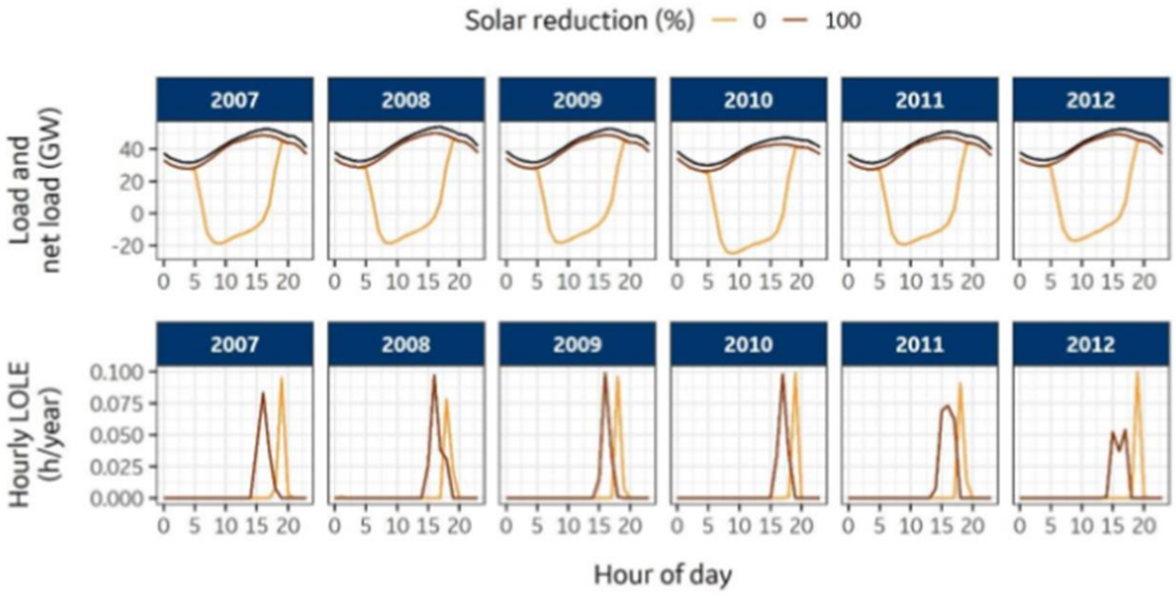




CAPACITY VALUE: Solar Reduction Sensitivities

- Reduction of solar in the system reduces the Capacity Value of PSH at lower storage durations
- Biggest effect shown in CA where PSH CV only reaches ~95% with 4 hours of storage with no solar in the system
- Reduction of solar removes the duck curve, makes risky hours spread across multiple hours, so 1 hour of storage is no longer sufficient to cover all the LOLE





As solar is taken out, PSH needs more storage duration to get to 100 CV

STUDY RESULTS AND CONCLUSIONS

- A **novel PSH Scheduling tool** was developed and for the first time incorporated the impact of variable height differences between reservoirs (‘head’) and variable speed machine behavior.
- **PSH has a positive impact** on reducing production cost, CO_2 emission and curtailment of other renewables in all scenarios even when competing with other storage.
- Two **new VSPSH stability models** have been created and incorporated into PSLF grid planning software so grid operators can assess their benefits.
- **Grid Resiliency**: A 2GW VSPSH plant in Arizona in *pumping mode* was able to markedly improve the frequency response by 50mHz in the US Western Interconnect.
- **Reserve Adequacy**: PSH has substantial capacity value even with short duration.
- Full report can be found at https://www.osti.gov/servlets/purl/1824300

PSH provides value to support power grid needs for generation adequacy, balancing, resiliency and stability.

New tools and methods are now available and being deployed to unlock that value.

Project Team

US Department of Energy

Alejandro Moreno

Rajesh Dham (Program Manager)

Hill (William) Balliet

Patrick Soltis

Sam Bockenhauer

Katie Jackson

GE Global Research

Miaolei Shao (Program Manager)

Xian Guo

GE Energy Consulting

Christina Bisceglia (Project Manager)

Eduardo Ibanez

Shruti D. Rao

Slobodan Pajic

Mitchel Bringolf

GE Renewable Energy

David Havard