# Modeling and Simulation of Advanced Pumped-Storage Hydropower Technologies and their Contributions to the Power System

**Vladimir Koritarov**, Argonne National Laboratory, U.S.A.
**Tao Guo**, Energy Exemplar, LLC, U.S.A.
**Erik Ela**, National Renewable Energy Laboratory, U.S.A.
**Bruno Trouille**, MWH Americas, Inc., U.S.A.
**James Feltes**, Siemens PTI, Inc., U.S.A.
**Michael Reed**, U.S. Department of Energy, U.S.A.

## Abstract

With the larger penetration of variable renewable energy resources, the role of energy storage in the power system is becoming increasingly important. The flexibility of operation of hydro and pumped-storage power plants and the variety of ancillary services that they provide to the grid enable better utilization of variable renewable resources and more efficient and reliable operation of the entire power system. The U.S. Department of Energy's Water Power Program has funded a recent study to enhance the modeling and simulation of advanced pumped-storage hydropower (PSH) technologies and examine the value of different services and contributions that they can provide to the power system. The technical approach consisted of two main components: (1) advanced technology modeling and (2) detailed production cost and revenue simulations.

The advanced technology modeling focused on the development of dynamic simulation models for advanced PSH technologies, such as adjustable-speed (AS) and ternary units. These new models were developed as vendor-neutral models and published during the course of the project.

The production cost and revenue simulations focused on the Western Interconnection (WI). The analyses were performed for the entire WI, for the California electricity market, and for a single balancing authority, the Sacramento Municipal Utility District. The goal of the study was to provide a comprehensive evaluation of PSH plants and their contributions to the power system. The project team has used several computer tools, including the PSS®E, FESTIV, CHEERS, and PLEXOS models, to simulate system operation and contributions of PSH plants. Advanced PSH technologies, i.e., AS and ternary units, were also modeled. Detailed modeling and simulation studies were performed using different time steps ranging from a fraction of a second to one hour. This paper provides an overview of the simulations performed during the study and some key results of the analyses.

## 1 Introduction

A project team, led by Argonne National Laboratory (Argonne), was tasked by the U.S. Department of Energy (DOE) to study the role and value of advanced pumped-storage hydropower (PSH) in the United States. The study was funded by DOE's Office of Energy Efficiency and Renewable Energy (EERE) through a program managed by the EERE's Wind and Water Power Technologies Office. In addition to Argonne, the project team included Siemens PTI, Inc., Energy Exemplar, LLC, MWH Americas, Inc., and the National Renewable Energy Laboratory (NREL).

The project team was supported and guided by an Advisory Working Group (AWG) consisting of 35 experts from a diverse group of organizations including the hydropower industry and equipment manufacturers, electric power utilities and regional electricity market operators, hydro engineering and consulting companies, national laboratories, universities and research institutions, hydropower industry associations, and government and regulatory agencies.

The main purpose of the study was to develop detailed simulation models of advanced pumped-storage technologies in order to analyze their technical capabilities to provide various grid services and to assess the value of these services under different market structures and for different levels of renewable generation resources integrated within the power system.

Although the existing dynamic models for conventional fixed-speed PSH plants provide accurate representation and modeling of these technologies, it was necessary to develop dynamic models of advanced PSH technologies (adjustable-speed [AS] and ternary PSH units), which were not available in the U.S. These new models would provide for accurate modeling of dynamic responses of the advanced PSH units to various system disturbances, and are needed for transmission interconnection studies of new PSH projects. In addition, one goal of the study was to improve the modeling representation of advanced PSH plants in production cost and power system operations simulation models, especially for high-resolution simulations performed with sub-hourly simulation time steps. While most production cost models can accurately simulate PSH technologies when using an hourly simulation time step, there is a need to improve these technologies' modeling representations and properly capture their flexible operating characteristics in high-resolution simulations. This was also one of the findings and recommendations in a recent EPRI report [1].

Another goal of the study was to perform production cost and revenue simulations and assess the role and value of various services and contributions that PSH technologies provide to the power system. The production cost and revenue simulations focused on the electric power systems within the Western Interconnection (WI), which covers the western part of the United States, the Canadian provinces of British Columbia and Alberta, and the Comisión Federal de Electricidad service area of northern Mexico. The analysis focused on several geographical areas within the region and was carried out for different levels of renewable energy generation in the power system. The analysis examined the benefits and value of PSH plants in both regulated and competitive electricity market environments.

# 2 Technical Approach

The scope of work for the study had two main components:

1. Development of vendor-neutral dynamic simulation models for advanced PSH technologies, and
2. Production cost and revenue analyses to assess the value of PSH in the power system.

To perform these tasks, the project team established several task force groups (TFGs) to focus on specific aspects of the modeling and/or analysis. In addition, the project team closely coordinated the work on the study with DOE and the AWG.

The first component of the study, development of vendor-neutral models, was carried out by the Advanced Technology Modeling TFG led by experts from Siemens PTI, with the participation of experts from other project team organizations. The Advanced Technology Modeling TFG first conducted a review of dynamic PSH and conventional hydro (CH) simulation models that are currently in use in the United States to determine whether improvements were needed. It was found that the existing dynamic models for conventional PSH and CH plants accurately describe their dynamic behavior and responses to system disturbances. The TFG then focused on the needs for new models and developed vendor-neutral models for advanced PSH technologies (AS and ternary PSH units) for which no dynamic models were available in the U.S. The new models were integrated into the PSS®E software and tested using the standard PSS®E test cases as well as the dynamic PSS®E cases for the WI developed by the Western Electricity Coordinating Council (WECC). The new dynamic models for AS and ternary PSH units were added to the PSS®E library of dynamic models and will be available to all PSS®E users. In addition, as these models were developed to be vendor-neutral, they were published in several of the reports for this project and are now available for integration into other software packages.

The simulations performed during the study addressed a wide range of power system operational issues and time frames, as illustrated in Figure 1. The analysis aimed to capture PSH behavior and operational characteristics across different time scales, from a fraction of a second for dynamic responses to annual simulations for production cost runs. The project team used a suite of four computer models (PSS®E, FESTIV, CHEERS, and PLEXOS) to simulate system operation and analyze various operational issues occurring on different time scales. This is illustrated in Figure 1, which also shows an approximate zone of wind/solar impacts and the system control issues that are mostly affected by the variability of these renewable energy resources.

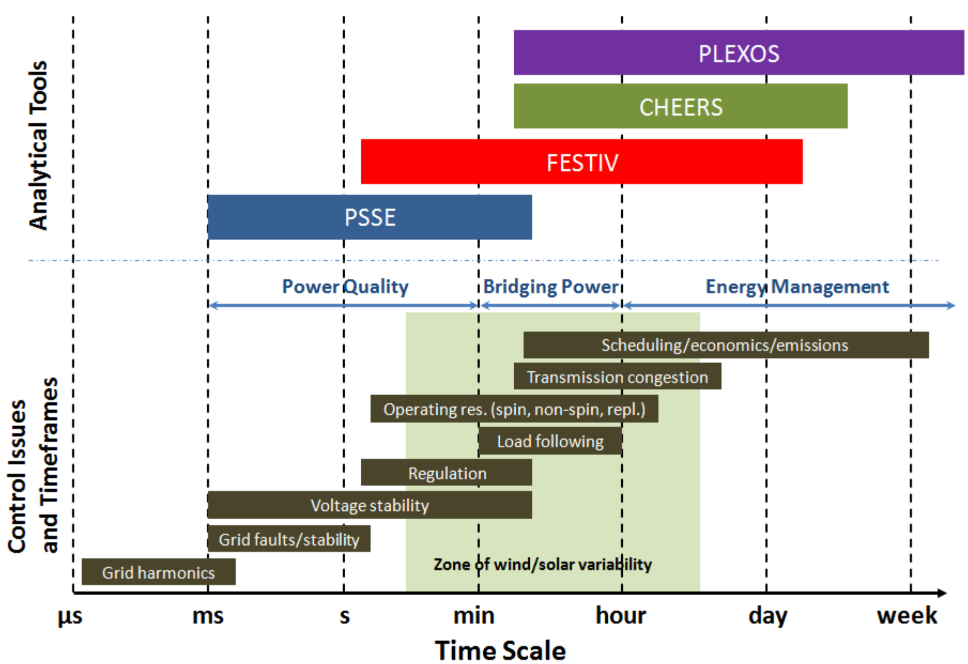


**Figure 1 Power System Time Frames and Operational Issues**

For the production cost and revenue modeling component of the study, the project team first developed a matrix of contributions and services that PSH plants provide to the system (Table 1). The Market Issues TFG was tasked with analyzing current operation and market treatment of PSH plants in regulated and restructured markets, while the Simulation TFG implemented the design of modeling cases and scenarios to address various PSH contributions and their value in different power systems.

**Table 1 PSH Services and Contributions**

| | 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 (VERs) |
| 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 |

The focus of the study was on the WI; however, the geographical scope included modeling both the entire WI and different balancing authorities within the WI, as well as individual projects. Both cost-based and market-based approaches were applied in the analysis. The cost-based approach allows for the evaluation of benefits provided by PSH plants to the power system and is typically applied in the case of PSH projects operating in traditional vertically integrated utilities. On the other hand, the market-based approach allows for the calculation of revenues that a PSH project can realize in a restructured electricity market, where a PSH plant competes to provide energy and ancillary services. Thus, the market-based approach mainly focuses on the revenue streams that a PSH project may realize in a competitive market environment, depending on the available market mechanisms that have been established for different types of services. The main distinction between the cost- and market-based approaches in the evaluation of PSH plants is that the cost-based approach is a system-level approach where the value of a PSH project is measured by the overall benefits that it provides to the power system in which it operates, while the market-based approach focuses on the PSH plant and its potential revenues, thus providing information for the analysis of the financial viability of the PSH project in a competitive market environment.

The simulations of system operations were performed for a future year that was largely based on WECC's long-term projections for year 2022. WECC's Transmission Expansion Planning Policy Committee (TEPPC) 2022 Common Case served as the foundation for building modeling cases and scenarios, but certain case parameters and data varied depending on the scenario assumptions. Simulations of power system operations were performed for two levels of renewable energy penetration:

1. **Baseline Renewable Energy Scenario** – Corresponding to mandated Renewable Portfolio Standard levels of renewable energy generation, amounting to about 14% of total generation within the U.S. part of the WI in 2022; and
2. **High Wind Renewable Energy Scenario –** Corresponding to the High Wind Scenario from the *Western Wind and Solar Integration Study – Phase 2* [2], amounting to about 33% of renewable energy generation within the U.S. part of the WI in 2022.

For the fine-granularity simulations with time steps on the order of seconds, it was necessary to have high-resolution wind and solar data. Because the highest available resolution of wind and solar data was 10-minute data, the project team developed and utilized algorithms for generating synthetic second-by-second data streams. These algorithms use techniques like fractal analysis and cubic spline fit to interpolate higher-resolution data points within an existing stream of wind or solar data, using the pattern observed in actual high-resolution samples.

# 3 Summary of Key Findings

The study involved numerous simulations and model runs across various time scales. The key findings and conclusions derived from various analyses are summarized in the following subsections.

## 3.1 Advanced Technology Modeling

***Development and Testing of Dynamic PSH Models***

Dynamic models for AS and ternary units were developed as vendor-neutral models and described in several project reports that are publicly available [3–7]. The models were also integrated into the Siemens PTI's PSS®E software and added to the PSS®E library of dynamic models. In addition, the vendor-neutral models (block diagrams and transfer functions) were made publicly available for integration into other software tools.

The project team used the dynamic models of AS and ternary PSH units to conduct various power system dynamic performance studies and analyze dynamic behavior of these technologies and their impact on the power system. Also, analyses of conventional fixed-speed (FS) and advanced AS PSH technologies and their dynamic responses were studied for various system disturbances, including over- and under-frequency events due to sudden loss of load or generation in the power system, as well as to changes in the power generated by variable renewable energy sources. Compared to the conventional FS PSH plants, the analyses showed that the advanced PSH technologies provide greater flexibility and faster response times in response to system disturbances.

The testing of the dynamic models demonstrated that the new models perform well and can be used for typical dynamic simulation analyses required by transmission planning and interconnection studies. The tests also demonstrated the new capabilities available in these models, such as the use of AS and ternary PSH plants to provide regulation service in pump mode. For all scenarios and disturbances, the newly developed models of AS and ternary PSH units showed expected performance and allowed demonstration of the expected advantages of the advanced PSH technology, specifically the capability of AS pumps and ternary pumps to participate in secondary frequency control.

## 3.2 Production Cost Simulations using PLEXOS Model

Energy Exemplar's PLEXOS model was used to perform production cost and revenue simulations for the Base and High Wind renewable energy scenarios, with and without FS and AS PSH plants modeled in the system. The day-ahead (DA) simulations were performed on an hourly basis for the entire year 2022 for all cases. However, higher-resolution PLEXOS three-stage simulations with a 5-minute simulation time step were performed in each case for four typical weeks in year 2022, i.e., the third week in January, April, July, and October.

The analysis focused on three areas: WI, California, and the Sacramento Municipal Utility District (SMUD). In the WECC TEPPC database [8], the SMUD load region represents the Balancing Authority of Northern California (BANC).

Both cost-based and market-based approaches were used in the analysis. While the cost-based approach was applied for the simulation of the entire WI and for the SMUD footprint, a market-based approach (as a bid-based electricity market) was applied for the simulation of the California footprint.

### 3.2.1 Annual Simulation Results

The following sub-sections present some of the key results obtained from the annual PLEXOS simulations of the WI, California, and SMUD for three cases: (1) without any PSH plants, (2) with the existing FS PSH plants, and (3) with the existing FS and additional AS PSH plants. All three cases have been run for the Base and High Wind renewable energy scenarios.

***Production Cost Savings***

Table 2 summarizes the savings in total system production cost in 2022 that can be attributed to PSH capacity and demonstrates that production cost savings are greater for higher penetration of renewable energy resources in the system (High Wind renewable energy scenario).

The simulation results for the WI show that the existing FS PSH plants reduce total system operating cost in 2022 by about 1.1% (about $167 million) under the Base renewable energy scenario, or about 2% (about $248 million) under the High Wind scenario. The addition of three proposed AS PSH plants, Eagle Mountain, Iowa Hill, and Swan Lake North, could further reduce total production cost in the WI by an additional 1%, or $144 million, under the Base renewable energy scenario and by an additional 1.8%, or $229 million, under the High Wind scenario. Percentagewise, even larger cost savings could be achieved in California, where the FS and AS PSH capacity reduces total system operating costs by 3.4%, or $171 million, under the Base renewable scenario, and by a total of 9.1%, or $376 million, under the High Wind scenario.

**Table 2 Production Cost Savings (%) in 2022 due to PSH Capacity**

| Production Cost Savings Due to PSH Capacity (%) | Western Interconnection | | California | | SMUD | |
|---|---|---|---|---|---|---|
| | Base Renewable Energy Scenario | High Wind Renewable Energy Scenario | Base Renewable Energy Scenario | High Wind Renewable Energy Scenario | Base Renewable Energy Scenario | High Wind Renewable Energy Scenario |
| **With FS PSH** | 1.14 | 1.96 | 2.18 | 4.52 | - | - |
| **With FS & AS PSH** | 2.11 | 3.77 | 3.36 | 9.12 | 8.62 | 16.45 |

Results for the SMUD area show that the addition of the proposed Iowa Hill AS PSH plant could result in annual production cost savings of about $23 million, or 8.6% of the total SMUD production cost, under the Base renewable energy scenario; and in savings of about $51 million, or 16.45%, under the High Wind scenario.

### *Energy Arbitrage*

PLEXOS simulations of the California system in 2022 were performed using the market-based approach, which allows for detailed analysis of the value of energy arbitrage based on the locational marginal price (LMP) of electricity in each hour of the year. It should be noted that PLEXOS simulations were performed using the co-optimization of energy and ancillary services, so the results for energy arbitrage with ancillary services are likely different from the results obtained if the PSH operations were optimized to maximize the energy arbitrage revenues only. A summary of key PLEXOS results for the Base and High Wind renewable-energy scenarios is presented in Table 3.

**Table 3 Results for PSH Energy Arbitrage Revenues in California in 2022**

| | Base Renewable Energy Scenario | | High Wind Renewable Energy Scenario | |
|---|---|---|---|---|
| | FS PSH | FS&AS PSH | FS PSH | FS&AS PSH |
| **PSH Capacity (MW)** | 2,626 | 4,425 | 2,626 | 4,425 |
| **Energy Generation (GWh)** | 2,725 | 5,313 | 5,299 | 9,456 |
| **Pumping Energy (GWh)** | 3,840 | 6,856 | 7,501 | 12,521 |
| **PSH Capacity Factor (%)** | 11.85 | 13.71 | 23.04 | 24.39 |
| **Energy Revenue ($1,000s)** | 102,302 | 181,554 | 147,285 | 217,302 |
| **Pumping Cost ($1,000s)** | 65,768 | 164,508 | -13,229 | 25,045 |
| **Net Revenue ($1,000s)** | 36,534 | 17,046 | 160,514 | 192,257 |
| **Net Revenue ($/kW-yr)** | 13.9 | 3.9 | 61.1 | 43.4 |

The high penetration of variable energy resources (wind and solar) under the High Wind scenario keeps the average LMPs low and even negative when there are curtailments of excess variable generation. The cost of pumping energy for FS PSH plants under the High Wind scenario is negative because the pumping energy is mostly supplied by the excess VER generation that would have been curtailed. Table 3 also shows that the capacity of existing FS PSH plants would not be sufficient for the high level of renewable resources in the system. With the addition of AS PSH plants, the overall pumping cost under the High Wind scenario becomes positive, but its relatively low value indicates that the PSH pumping energy is still mostly comprised of the VER generation that would have been curtailed.

Table 3 also shows that, under the High Wind scenario, the addition of AS PSH plants increases the total annual net revenues from energy arbitrage; however, the net revenues per kW of PSH capacity are smaller because of the much larger PSH capacity in the system.

***Operating Reserves***

Figures 2 and 3 illustrate the contributions of PSH plants to operating reserves in the WI and California power systems in 2022. The results are presented for both the Base and High Wind renewable energy (RE) scenarios. Taking into account that the combined capacity of FS and AS PSH plants represents less than 3 percent of the total WI system capacity in 2022, it can be observed that PSH plants provide a significant amount of operating reserves to the system, especially in cases when both FS and AS PSH plants are in operation. Also, it can be noted that PSH contributions to operating reserves increase significantly with the addition of AS PSH plants to the system.

An especially large increase is observed for the regulation down and flexibility down reserves, because the AS PSH can provide these services in the pumping mode of operation as well. These reserves are especially needed during times of low flexibility in the power system, such as during the night.

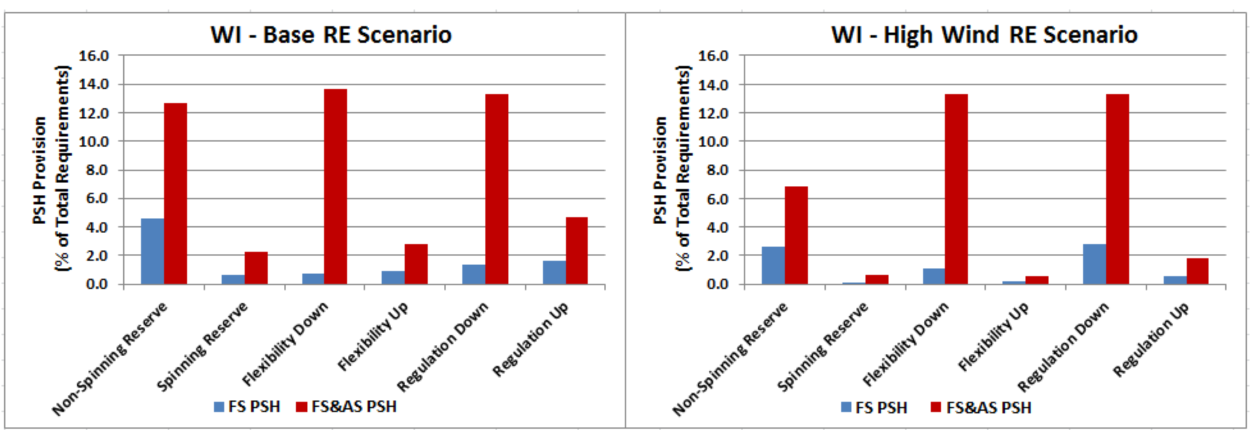


**Figure 2 PSH Contributions to Western Interconnection Operating Reserves in 2022**

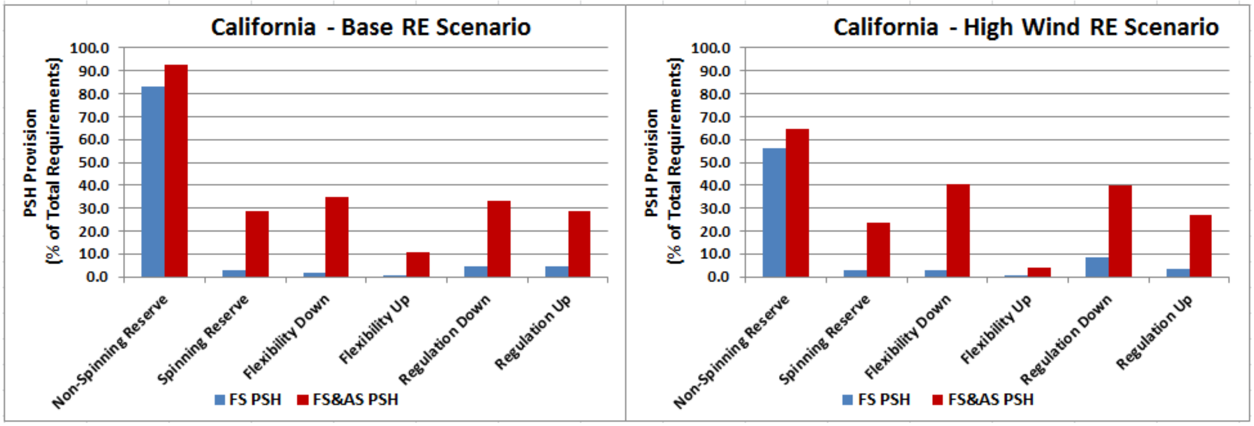


**Figure 3  PSH Contributions to California Operating Reserves in 2022**

With regard to the monetary value of PSH contributions to operating reserves, PLEXOS simulations for California were performed using a market-based approach, which allowed for individual pricing and revenue analysis of ancillary services. A summary of PSH total annual revenues attributable to their contributions of operating reserves in 2022 is provided in Table 4.

**Table 4  PSH Revenues from Contributions of Operating Reserves in California in 2022**

| Operating Reserve | Base Renewable Energy Scenario | | High Wind Renewable Energy Scenario | |
|---|---|---|---|---|
| | FS PSH ($1,000s) | FS&AS PSH ($1,000s) | FS PSH ($1,000s) | FS&AS PSH ($1,000s) |
| Non-Spinning Reserve | 7,557 | 8,563 | 5,246 | 6,184 |
| Spinning Reserve | 1,218 | 8,588 | 1,515 | 6,208 |
| Flexibility Down | 389 | 5,728 | 1,626 | 14,934 |
| Flexibility Up | 43 | 731 | 80 | 412 |
| Regulation Down | 4,562 | 20,360 | 19,511 | 49,885 |
| Regulation Up | 4,436 | 7,935 | 4,144 | 8,528 |
| TOTAL | 18,205 | 51,905 | 32,122 | 86,151 |

The revenues attributable to PSH plants from their contributions of operating reserves can also be expressed per kW of PSH capacity. The results presented in Table 5 show that the highest average annual revenues are from the provision of regulation down service.

**Table 5 Average Annual PSH Revenues from Operating Reserves in California in 2022**

| Operating Reserve | Base Renewable Energy Scenario | | High Wind Renewable Energy Scenario | |
|---|---|---|---|---|
| | FS PSH ($/kW-yr) | FS&AS PSH ($/kW-yr) | FS PSH ($/kW-yr) | FS&AS PSH ($/kW-yr) |
| Non-Spinning Reserve | 2.88 | 1.94 | 2.00 | 1.40 |
| Spinning Reserve | 0.46 | 1.94 | 0.58 | 1.40 |
| Flexibility Down | 0.15 | 1.29 | 0.62 | 3.37 |
| Flexibility Up | 0.02 | 0.17 | 0.03 | 0.09 |
| Regulation Down | 1.74 | 4.60 | 7.43 | 11.27 |
| Regulation Up | 1.69 | 1.79 | 1.58 | 1.93 |
| **TOTAL** | **6.93** | **11.73** | **12.23** | **19.47** |

### *Integration of Variable Energy Resources*

PSH plants enable larger penetration of VER in the power system by providing a large quantity of very flexible system capacity that can be used to compensate for the variability and uncertainty of VER generation. In addition, the operating characteristics of PSH plants, which have quick ramping capabilities and can provide large quantities of operating reserves to the system, make them ideally suited to support VER generation.

PLEXOS simulation results for the WI under the Base renewable energy scenario show that the FS PSH plants reduce curtailments of VER generation by 565 GWh, or about 29% of total curtailments if there were no PSH plants operating in the system. With both FS and AS PSH plants operating in the WI system, the curtailments are reduced by 958 GWh, or about 50% of total curtailments. The amount of curtailed VER generation under the High Wind scenario is much greater and amounts to 56,885 GWh in the case without PSH plants operating in the system. The FS PSH plants reduce this curtailment by 8,482 GWh, or 15%, while when both FS and AS PSH plants are operating in the system, the curtailments are reduced by 12,675 GWh, or 22%. Assuming a 30% capacity factor, the savings of 12,675 GWh roughly correspond to an average annual generation of almost 5,000 MW of wind capacity.

In California, under the Base renewable energy scenario, the curtailments of VER generation are reduced from 155 GWh in the case without PSH plants to 46 GWh (70% reduction) if FS PSH are operating in the system, and to 14 GWh (91% reduction) if both FS and AS PSH are operating. Under the High Wind scenario, the curtailments are reduced from 618 GWh in the case without PSH plants to 380 GWh (39% reduction) if FS PSH plants are operating in the system, to 275 GWh (55% reduction) if both FS and AS PSH plants are operating.

The results for the SMUD footprint show that the addition of the Iowa Hill AS PSH plant reduces renewable energy curtailments from 19 GWh to 1 GWh (95% reduction) under the High Wind renewable energy scenario. There were no curtailments of VER generation under the Base renewable energy scenario.

***Reduced Cycling of Thermal Generating Units***
The flexibility of PSH capacity, its fast ramping characteristics, and load-leveling operation create a flatter net load profile for thermal generating units, which allows them to operate in a steadier mode, thus reducing the need for their ramping and frequent startups and shutdowns.

*Reduced Startup Costs*
As startups and shutdowns of thermal generating units involve substantial operating costs, as well as increased wear and tear on the units, a reduction in the number of unit startups provides for significant savings in system operating costs. PLEXOS results show that under both renewable energy scenarios, the number of starts and startup costs of thermal generators are reduced substantially as more PSH capacity is introduced into the system.

If both FS and AS PSH plants are operating in the system, the annual thermal startup cost savings for the WI amount to $44 million (about a 28.6% reduction in system startup costs) under the Base renewable energy scenario, and $31 million (about 17.7% savings) under the High Wind scenario. Figure 4 illustrates the percentage reductions in thermal startup costs due to PSH capacity in the WI.

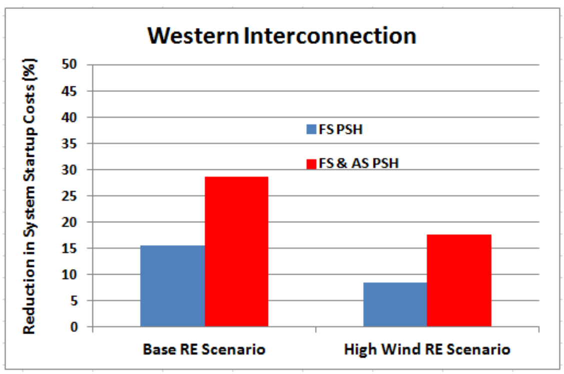


**Figure 4 Reduction in Thermal Startup Costs due to PSH Capacity in the WI in 2022**

In the case of California, the savings in startup costs are similar under both renewable energy scenarios, and amount to about $10 million if only the existing FS PSH plants are operating in the system and to about $20 million if both FS and AS PSH plants are operating. The reductions in startup costs, as percentages of total startup costs in California, are illustrated in Figure 5.

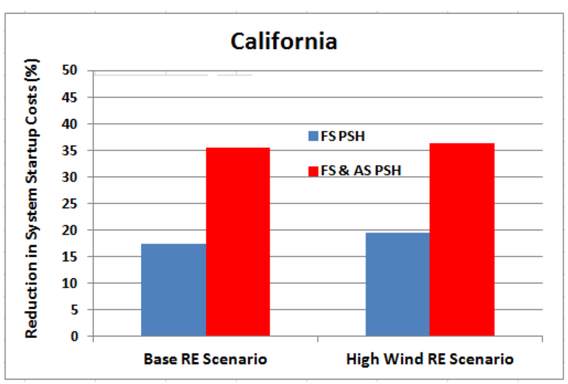


**Figure 5 Reduction in Thermal Startup Costs due to PSH Capacity in California in 2022**

In the case of SMUD, the addition of the AS PSH plant (Iowa Hill) reduces annual startup costs by about $2 million under both renewable energy scenarios. As a percent of total system startup costs in 2022, the cost savings ($2 million) represent about 45% of total startup costs under the Base and about 42% under the High Wind renewable energy scenario. These results are illustrated in Figure 6.

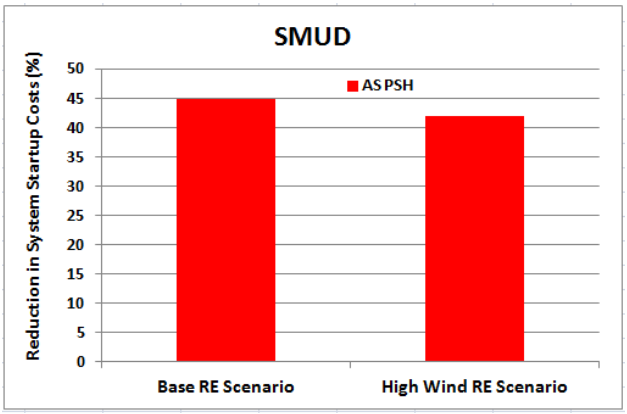


**Figure 6 Reduction in Thermal Startup Costs due to PSH Capacity in SMUD in 2022**

*Reduced Thermal Generator Ramping*

Figures 7 through 9 present the results for reductions in thermal generator ramping (both up and down) in the WI, California, and SMUD systems, respectively.

PLEXOS simulations for the WI in 2022, under the Base renewable energy scenario, show that FS PSH plants reduce the total ramp-up needs of thermal generators during the year by 1,786 GW, and ramp-down needs by 2,560 GW. These values represent aggregated ramping MWs of all units in all hours of the year. If both FS and AS PSH plants are operating in the system, the ramp-up needs of thermal generators are reduced by 3,420 GW and ramp-down needs by 4,817 GW.

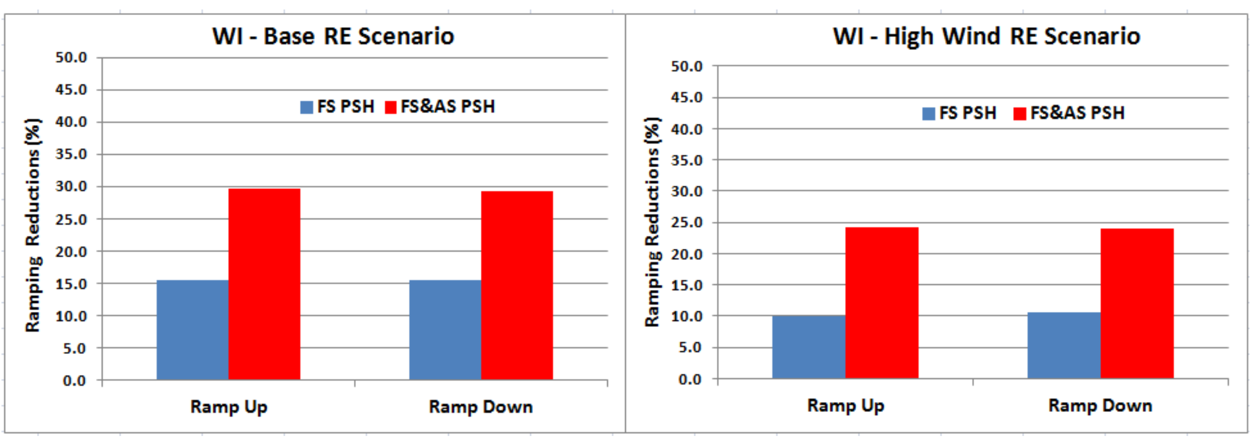


**Figure 7 Reductions in Thermal Capacity Ramping Needs in WI in 2022 due to PSH Capacity**

Similarly, the results for California in 2022, under the High Wind renewable energy scenario, show that FS PSH plants reduce the ramp-up and ramp-down needs of thermal generators by 531 GW and 945 GW, resepctively. If both FS and AS PSH plants are operating in the system, the ramp-up and ramp-down needs of thermal generators are reduced by 1,214 GW and 1,943 GW, respectively.

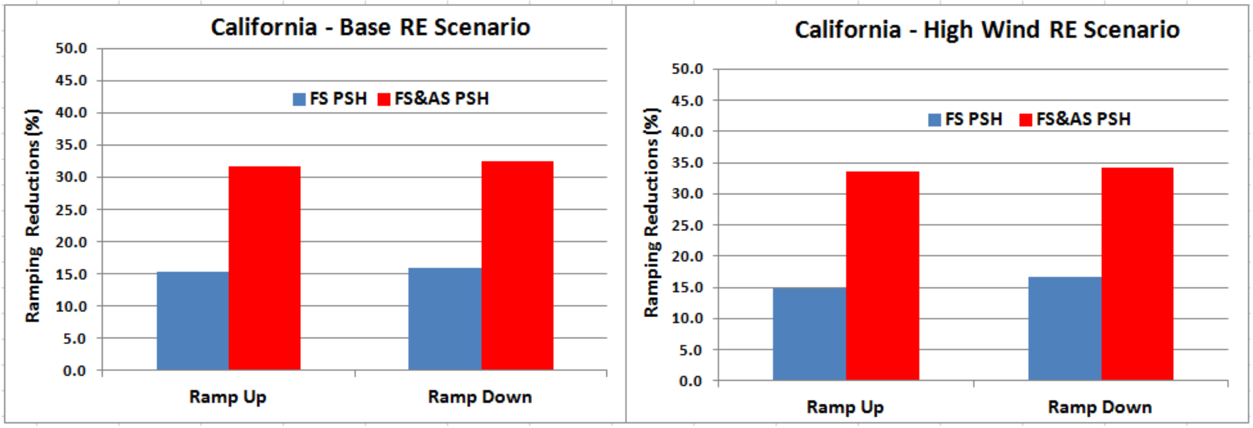


**Figure 8 Reductions in Thermal Capacity Ramping Needs in California in 2022 due to PSH Capacity**

In the case of the SMUD, the proposed AS PSH plant (Iowa Hill) reduces ramp-up and ramp-down needs by 136 GW and 197 GW, respectively, under the Base renewable energy scenario, and by 119 GW and 174 GW, respectively, under the High Wind scenario

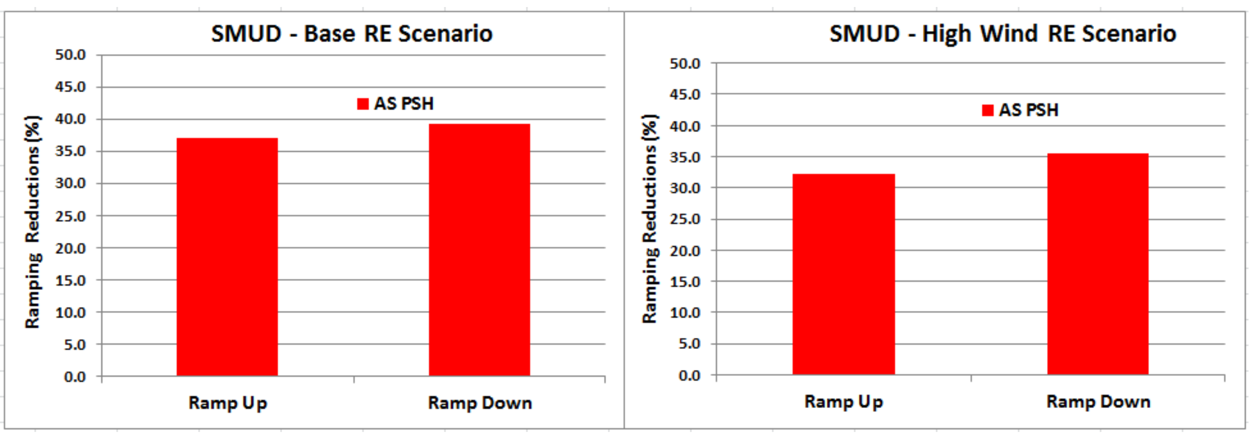


**Figure 9 Reductions in Thermal Capacity Ramping Needs in SMUD in 2022 due to PSH Capacity**

***PSH Impacts on Power System Emissions***

Simulation results for the WI (Figure 10) show an increase in $CO_2$, $NO_x$, and $SO_2$ emissions under the Base renewable energy scenario, but the operation of PSH plants decreases overall system emissions under the High Wind scenario. This is primarily due to a higher percentage of wind energy that is available for PSH pumping and the PSH impacts on reducing the curtailments of wind energy, which offset the increased emissions of conventional thermal generating units.

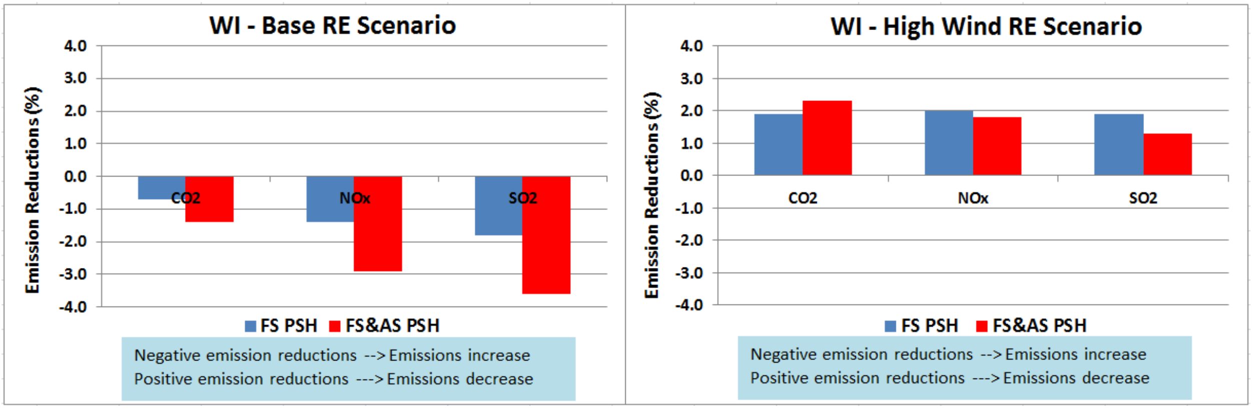


**Figure 10 Emission Reductions due to PSH Capacity in Western Interconnection in 2022**

The results for California (Figure 11) show a decrease in $CO_2$ and $NO_x$ emissions and an increase in $SO_2$ emissions under both Base and High Wind renewable energy scenarios. The results for California are different from those obtained for the WI because of the differences in the generation mix of these two power systems.

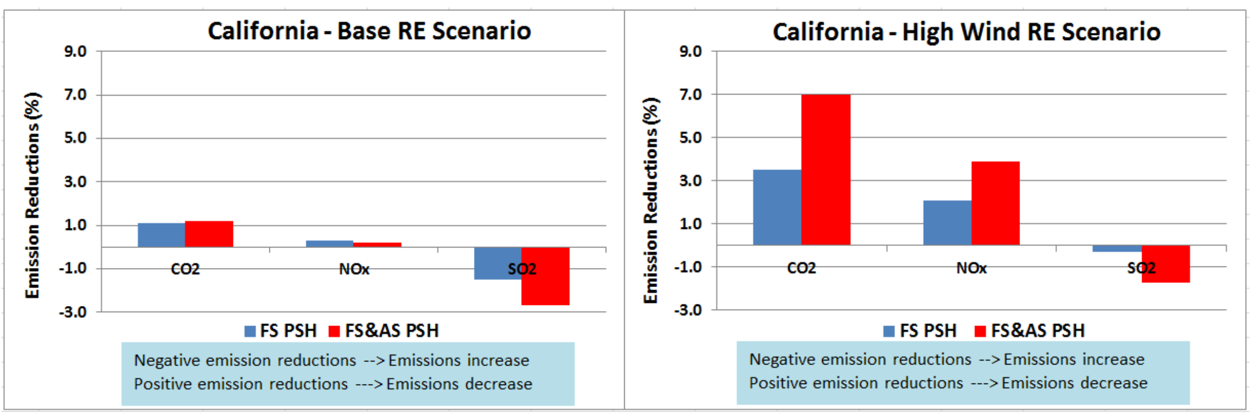


**Figure 11 Emission Reductions due to PSH Capacity in California in 2022**

The most significant emission reductions are observed for the SMUD system (Figure 12). The introduction of the proposed Iowa Hill AS PSH plant reduces pollutant emissions in the SMUD system under both renewable energy scenarios.

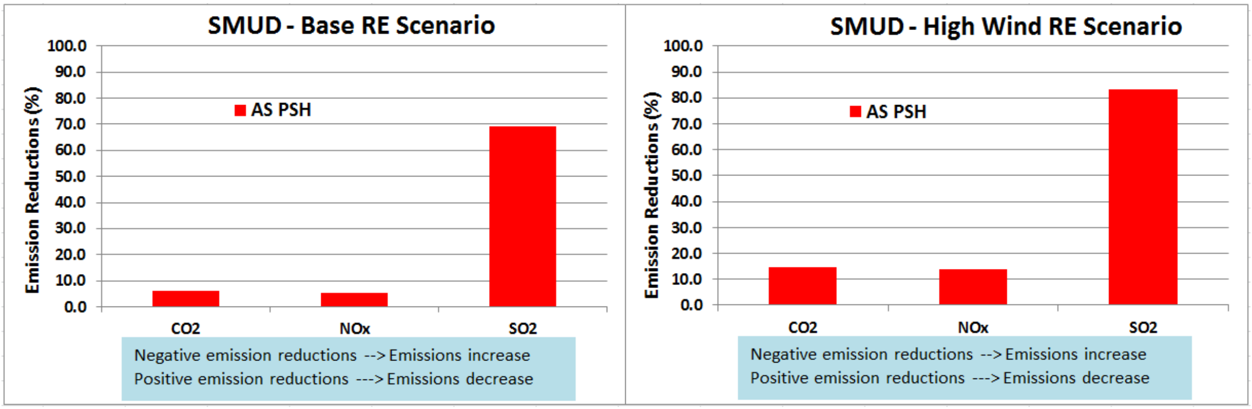


**Figure 12 Emission Reductions due to PSH Capacity in the SMUD System in 2022**

***PSH Impacts on Transmission Congestion***

In markets that use locational marginal pricing, there exists a component of the price that is based on transmission congestion. The transmission congestion price is an indicator of the congestion in the transmission grid. The lower transmission congestion prices obtained in cases with PSH plants indicate that they help mitigate the costs associated with transmission congestion.

PLEXOS simulations of the WI show that, under the Base renewable energy scenario, average transmission congestion prices decrease from $4/MWh in the case without PSH plants operating in the system to $2/MWh if both FS and AS PSH plants are operating. Because transmission expansion was enacted for the High Wind scenario, little congestion was seen with or without PSH and therefore no significant reductions of transmission congestion prices were observed under that scenario.

### 3.2.2 Three-Stage DA-HA-RT Simulation Results

To capture the uncertainty of renewable energy forecasting and intra-hourly variability of VER, as well as to evaluate system needs for operating reserves and flexible ramping capacity, three-stage DA-HA-RT (Day Ahead – Hour Ahead – Real Time) sequential simulations with a 5-minute time step in RT were performed for four typical weeks in different seasons of the year. Simulations were performed for the WI, California, and SMUD footprints, and the selected weeks were the third weeks in January, April, July, and October of 2022.

Table 6 presents a summary of key results obtained from 3-stage simulations for the WI, California, and SMUD power systems. The results shown are for the High Wind renewable energy scenario. SMUD plans the addition of an AS PSH plant (Iowa Hill) to its power system in the future; therefore, conventional FS PSH plants were not modeled in the simulations of the SMUD footprint.

The results of these detailed, high-resolution (5-minute time step) simulations show that the overall production cost savings due to operation of FS and AS PSH plants in the system amount to about 3.6% of the total production costs in the WI, 7.3% in California, and 14.3% in the SMUD system. Although these are the average cost savings over the four typical weeks in different seasons of 2022, the average annual values can be expected to be in a similar range. PLEXOS annual simulation runs using the hourly time step also provide similar results.

The impacts of PSH plants on reduction of startup and shutdown cost are also significant. The operation of FS and AS PSH plants in the system reduces overall startup and shutdown costs from about 11% in SMUD up to almost 42% in California.

Similarly, the operation of both FS and AS PSH plants reduces the need for ramping of thermal generating units. Over the four typical weeks in 2022, the ramping up and down of thermal units decreased by about 22–25% in the WI and SMUD areas. The reductions in ramping needs are even greater in California, with the ramping down of thermal units decreasing by more than 60%. These results demonstrate that PSH plants can manage a significant number of ramping duties to counterbalance the intra-hourly variations in loads and variable renewable generation.

**Table 6 Summary of PLEXOS 3-Stage Results for WI, California, and SMUD in 2022**

| High Wind Renewable Energy Scenario | Average Cost Savings or Decrease in Ramping Needs due to PSH Capacity over the Four Simulated Typical Weeks in 2022 | | | |
|---|---|---|---|---|
| | System Production Cost Savings (%) | Startup and Shutdown Cost 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 |

It should be noted that in the 3-stage simulations, the results of RT simulations show higher operating costs and ramping needs than those of the DA simulations. This is because the RT simulations capture the intra-hourly variability of VER generation, which is not captured by DA simulations that use hourly time steps. The higher operating cost and ramping needs of thermal generators in RT simulations indicate that they require additional ramping to meet the sub-hourly variability and uncertainties of load and variable renewable generation.

## 3.3 Analysis of Reliability and Costs using the FESTIV Model

NREL’s FESTIV model was utilized to analyze in high temporal detail how conventional and advanced PSH can assist in reducing total system production costs and improving steady-state reliability. The FESTIV model was used to simulate BANC, where the SMUD system is located, for two time periods—one with highly volatile variable generation and relatively low load in

April, and one with reduced variable generation but significant load in July. In both time periods, use of a conventional FS PSH plant reduced the total system production costs. With the addition of an AS PSH plant rather than the conventional FS PSH plant, production costs were further reduced. These results mirror those obtained from PLEXOS simulations and the analysis of detailed power system operations at multiple timescales demonstrates that conventional PSH and advanced PSH provide significant benefits to systems of this size by reducing production costs.

The FESTIV model was also used to evaluate the contributions of PSH plants to the reliability of power system operation. Tables 7 and 8 show FESTIV results for the impacts of FS and AS PSH plants on improving the reliability of and reducing energy imbalance in the BANC system. The simulations were performed using a 4-sec time step to model the real-time operation of the power system and calculate the area control error (ACE) and energy imbalances. A case without a PSH plant operating in the system served as the reference case.

The results of the analysis show that FS and AS PSH plants reduce the number of Control Performance Standard 2 (CPS2) violations and improve the CPS2 score in both the April and July weeks of 2022, but the effects are more significant during the July week. The results for the July week also show improvements in the absolute amount of ACE and the standard deviation of ACE.

**Table 7 Impacts of PSH on ACE and Steady-State Reliability in April 2022**
**(Third Week of April 2022, Balancing Authority of Northern California – BANC)**

| | (1) No PSH | (2) With FS PSH | (3) With AS PSH |
|---|---:|---:|---:|
| **Total Production Cost** | $3.449M | $3.169M | $3.032M |
| **Number of CPS2 Violations** | 49 | 47 | 45 |
| **CPS2 Score** | 95.1% | 95.3% | 95.5% |
| **Absolute ACE in Energy (AACEE)** | 2582.78 | 2619.72 | 2644.19 |
| **$\sigma_{ACE}$ [MW]** | 23.8 | 25.1 | 23.0 |

**Table 8 Impacts of PSH on ACE and Steady-State Reliability in July 2022**
**(Third Week of July 2022, Balancing Authority of Northern California – BANC)**

| | (1) No PSH | (2) With FS PSH | (3) With AS PSH |
|---|---:|---:|---:|
| **Total Production Cost** | $5.394M | $5.101M | $5.021M |
| **Number of CPS2 Violations** | 40 | 16 | 15 |
| **CPS2 Score** | 96.0% | 98.4% | 98.5% |
| **Absolute ACE in Energy (AACEE)** | 3201 | 2736 | 2593 |
| **$\sigma_{ACE}$ [MW]** | 29.3 | 21.3 | 20.2 |

These results also illustrate the impacts of PSH provisions of regulation reserve on improving the system reliability, which allows a balancing authority to better meet steady-state reliability standards. Figures 13 and 14 show the operation and power output levels of three FS PSH units and three AS PSH units, respectively, during one day in April 2022. From Figure 14, it can be observed that AS PSH units frequently provide regulation service in the pumping mode of operation and for this reason often pump with less than full capacity.

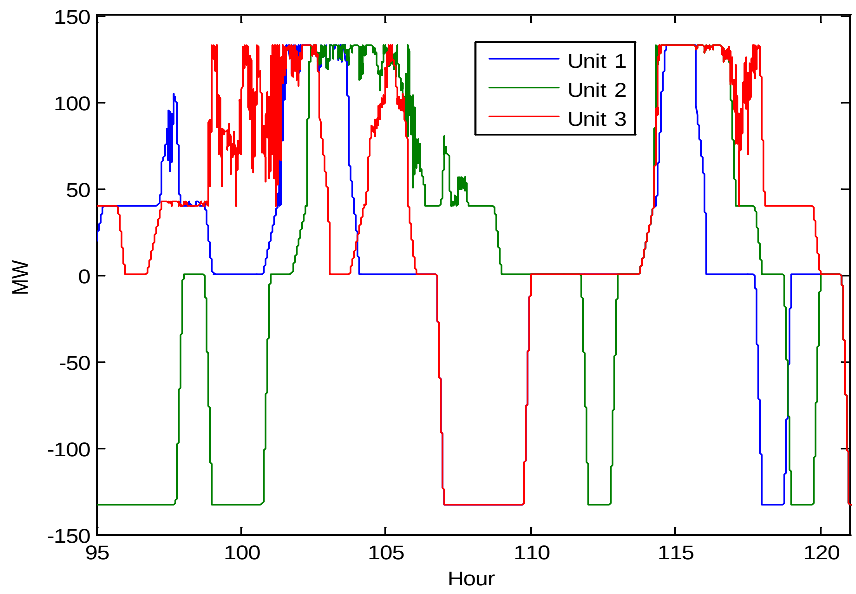


**Figure 13 Power Output of Three FS PSH Units for 1 Day in April**

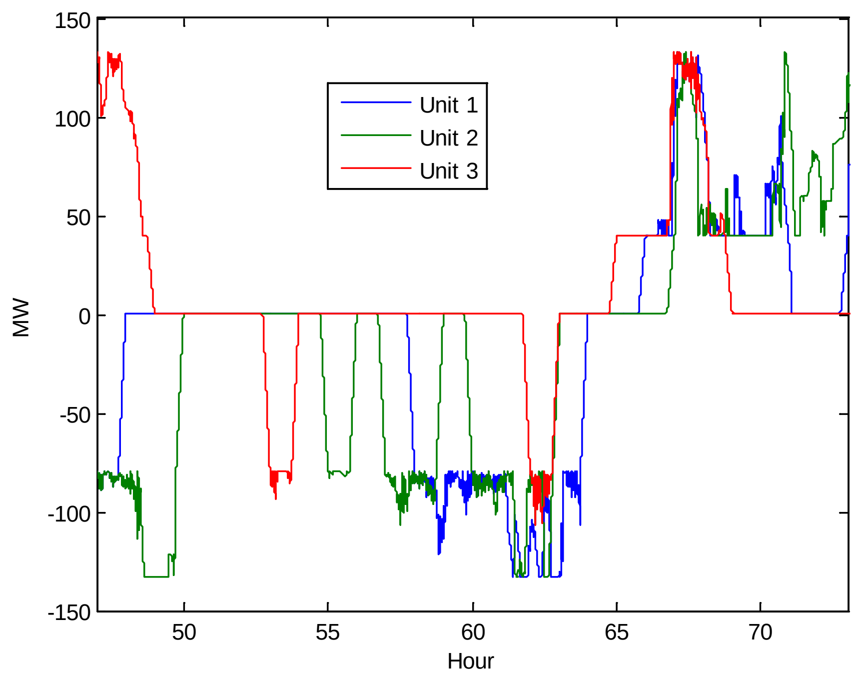


**Figure 14 Power Output of Three AS PSH Units for 1 Day in April**

# 4 Conclusions

Recognizing the need for better representation of PSH plants in power system simulation models, the project team developed new dynamic models for advanced PSH technologies (AS and ternary PSH units). The models were developed as vendor-neutral and, while integrated into the PSS®E model for the dynamic analyses performed during the study, the new models are also publicly available (as block diagrams and transfer functions) for integration into other software packages.

The project team also improved modeling representation of PSH plants in current state-of-the-art power system simulation tools (PLEXOS, FESTIV, and CHEERS) that are capable of high-resolution simulations of power systems using sub-hourly time steps.

The present study demonstrates that PSH plants provide a variety of benefits to the power system. While in the past the benefits of PSH plants were usually associated only with the energy arbitrage and contingency reserves, this study clearly shows that these are just a fraction of the total value that PSH plants provide to the system. Many of the PSH services and contributions are usually taken for granted, and for many of them there are no established mechanisms to provide revenues to PSH plants for providing those services or contributions to the power system.

The study shows that the value of PSH plants increases with higher penetration of VER in the system. In addition to enabling larger integration of VER technologies into the system and reducing the curtailments of excess variable generation, PSH plants reduce the overall system generation costs, provide flexibility and various operating reserves necessary for system operation, reduce cycling of thermal generating units and associated startup/shutdown and ramping costs, reduce transmission congestion, increase the reliability of system operation, and provide many other benefits. In addition, with a larger share of VER in the system, PSH plants tend to have a positive impact on system emissions, as a larger share of pumping energy is provided by VER generation.

Compared to the conventional FS PSH plants, the analyses showed that the advanced AS PSH technologies provide greater flexibility and faster response to system disturbances, allow for greater savings in overall system production costs, provide larger amounts of various operating reserves, and generally provide more value to the power system.

## Acknowledgment

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office, under contract DE-AC02-06CH11357.

## References

[1] EPRI, Quantifying the Value of Hydropower in the Electric Grid: Final Report, Palo Alto, Calif., February 2013.

[2] National Renewable Energy Laboratory, The Western Wind and Solar Integration Study Phase 2, Report, NREL/TP-5500-55588, September 2013.

[3] Argonne National Laboratory, Review of Existing Hydroelectric Turbine-Governor Simulation Models, Report, ANL/DIS-13/05, August 2013.

[4] Argonne National Laboratory, Modeling Adjustable Speed Pumped Storage Hydro Units Employing Doubly-Fed Induction Machines, Report, ANL/DIS-13/06, August 2013.

[5] Argonne National Laboratory, Modeling Ternary Pumped Storage Units, Report, ANL/DIS-13/07, August 2013.

[6] Argonne National Laboratory, Testing Dynamic Simulation Models for Different Types of Advanced Pumped Storage Hydro Units, Report, ANL/DIS-13/08, August 2013.

[7] Argonne National Laboratory, Simulation of the Secondary Frequency Control Capability of the Advanced PSH Technology and its Application to the SMUD System, Report, ANL/DIS-13/10, November 2013.

[8] WECC TEPPC, "*2022_CommonCase_InputAssumptions.doc.*"

## Authors:

**Vladimir Koritarov** is the Deputy Director of the Center for Energy, Environmental and Economic Systems Analysis at the Argonne National Laboratory. He has over 30 years of experience in the analysis of power system capacity expansion options, modeling of hydroelectric and irrigation systems, hydro-thermal coordination, reliability and production cost analysis, marginal cost calculations and electric sector restructuring issues. Mr. Koritarov has managed numerous energy and environmental projects and provided technical assistance to more than 30 countries. Before joining Argonne in 1991, Mr. Koritarov worked for eight years as a power system planner in the Union of Yugoslav Electric Power Industry.

**Tao Guo** has more than 25 years of working experience in power system planning, operation and control, especially in power market simulation software development, and consulting assignments in the areas of variable generation integration, energy imbalance market study, pumped-storage evaluation, portfolio optimization, and generation-transmission planning. He is now the Regional Director of West Coast, USA, at Energy Exemplar, supporting the applications of PLEXOS in North America, after having been the director of software development for 12 years at Global Energy (now Ventyx of ABB).

**Erik Ela** received his BSEE degree from Binghamton University and his MSEE degree from Illinois Institute of Technology. He is a senior engineer at the National Renewable Energy Laboratory and is an expert in the fields of power system modeling, power system operations, wholesale electricity market design, frequency control ancillary services, and the integration of renewable and emerging technologies into bulk power systems. Prior to joining NREL, Erik worked at the New York Independent System Operator as an engineer, improving operations procedures and market designs for the State of New York.

**Bruno Trouille** graduated in 1975 with an MS degree in Engineering from the Institut Catholique des Arts et Metiers in Lille, France. He also has an MS in Industrial Relations from Loyola University, Chicago, USA. He is a Vice President at MWH, working in the International Projects Group. He serves as senior project manager or lead economic and financial analyst on hydropower and pumped storage projects, power system expansion studies, regional market analyses, and project financing. He is often a speaker at conferences and has chaired a number of pumped-storage sessions.

**James W. Feltes** received his BSEE degree with honors from Iowa State University in 1979 and his MSEE degree from Union College in 1990. He joined PTI, now Siemens PTI, in 1979 and is currently a Senior Manager in the Consulting Department. At PTI, he has participated in many studies involving planning, analysis and design of transmission and distribution systems. He is an instructor in several of the courses taught by PTI. He is a member of several IEEE committees, working groups, and task forces dealing with power system stability and control. He is a Senior Member of the IEEE and is a registered professional engineer in the State of New York.

**Michael Reed** is the Program Manager/Chief Engineer for the Water Power Technologies Program in the Wind and Water Power Technologies Office of the Office of Energy Efficiency and Renewable Energy (EERE) at the U.S. Department of Energy. He has over 25 years of experience in power and propulsion systems, and currently manages DOE’s hydropower research and development efforts. Mr. Reed has a B.S. degree in Marine Engineering from the U.S. Merchant Marine Academy and an MS in Environmental Science and Policy from Johns Hopkins University.