WBS DE-EE0008781– Modeling and Optimizing Pumped Storage in a Multi-stage Large Scale Electricity Market under Portfolio Evolution

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Project Overview

Project Summary

- *Objective*: develop a prototype enhanced PSH model in the multi-stage market clearing process considering unique characteristics of PSH, and leverage its fast-ramping capability to provide great value to the grid.
- *Challenges*: utilizing the PSH flexibility to deal with realized uncertainties can cause deviation in the multi-stage processes and result in financial risks; state of charge (SOC) constraints of PSH needs to be continuously optimized.
- *Unique approach*: develop enhanced PSH model for incorporation into the multi-stage process and long-term planning; based on real plant efficiency data, actual large-scale electricity market data and high performance computing platform.

Intended Outcomes

- The project intends to develop an enhanced PSH model in the multi-stage market clearing process that can facilitate a deeper participation of PSH resources in organized electricity markets.
- Final products include a prototype day-ahead (DA) SCUC model with PSH optimization; a mathematical formulations to incorporate price forecasts for intra-day optimization; a planning model with improved realistic characteristics of PSH and the incorporation of market enhancement.

Project Information

Principal Investigator(s)

- Rui Bo, Missouri University of Science and Technology
- Yonghong Chen, MISO
- Lei Wu, Stevens Institute of Technology
- Ross Baldick, RBECS

Project Partners/Subs

- DTE Electric
- Consumers Energy
- Ameren

Project Status

Completed

Project Duration

- Project Start Date: 08/01/2019
- Project End Date : 08/31/2021

Total Costed (FY19–FY21)

$999,553

Project Objectives: Relevance

Relevance to Program Goals:

- The project helps to address one of the identified challenges “Untapped Potential for Hydropower and Pumped Storage to Support a Rapidly Evolving Grid”, and relates to the intermediate goal of *maximizing hydropower’s value for reliability, resilience, and integration*.
  - Through continuously optimizing PSH state of charge under uncertainties over multiple time horizons, the project explores PSH’s potential in increasing electricity market efficiency.
  - By developing generic and computational efficient methods, the project methods are applicable to other storage technologies and scalable to large scale electricity markets.
  - With direct involvement of MISO and industry partners, the project methods are already validated using real large-scale electricity market data. MISO considers incorporating the developed models from this project into production in the future, pending further extensive tests, stakeholder process and prioritization.
  - It enables greater utilization of PSH flexibility in multi-stage clearing process and facilitate a deeper market penetration of renewable and/or distributed energy resources.

Project Objectives: Approach

Approach:

- Day-ahead (DA)
  - Explore PSH optimization in day-ahead (DA) security constrained unit commitment (SCUC) to enable deeper participation of PSHs through offering their characteristics into the DA market, instead of reflecting SOC through schedules and offers.
  - Propose withholding of energy (energy reserve or MWh reserve) from energy-limited resources and stochastically determined SOC headroom to mitigate increased uncertainties from a changing portfolio.
- Intra-day
  - Create a framework to optimize PSH in intra-day operation and utilizes probabilistic price forecast to incorporate RT uncertainties.
- Planning
  - Propose model enhancements and correction for long-term planning analyses.
  - Use industry-grade tools, models, and realistic data to study, evaluate and quantify opportunities to improve the market design.

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

- Prototype Deterministic PSH model developed in SCUC
- Energy reserve requirements to compensate for uncertainties
- Mathematical formulations to incorporate price forecasts for PSH optimization
- Improved deterministic PSH model for planning
- Long-term value of optimized PSH operation

Outcomes:

- Reduced total system cost and increased PSH owner profit
- Developed models are computationally scalable and suitable for large-scale electricity market and power grid
- MISO considers incorporating the developed models into production in the future
- 11 journal papers have been published, and 4 technical presentations were made at IEEE and INFORMS meetings, and at FERC Technical Conference.

Project Timeline

Task Name	19 2020 2021 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Phase I	
Milestone 1: Prototype DA SCUC model with PSH optimization	
Milestone 2: Model with price forecasts for PSH optimization	
Milestone 3: Improved PSH model and Interleaved DA/RT simulation method for economic planning	
Milestone 4: MWh reserve requirement for SCUC	
Deliverable 5: prototype representation of price forecast uncertainty	
Milestone 6: Deterministic PSH optimization model with market enhancements for economic planning	
Critical Design Review	
Phase II	
Milestone 8: Prototype stochastic SCUC tool	
Deliverable 9: Test results of prototype SCUC and long-term value of enhanced PSH model	

- A no-cost extension was approved and the project end date was extended to August 31, 2021.

Project Budget

Total Project Budget – Award Information		
DOE	**Cost-share**	**Total**
$999,553	$ 250,172	$1,249,725

FY19	FY20	FY21	Total Actual Costs FY19–FY21
Costed	**Costed**	**Costed**	**Total Costed**
$0	$249,666	$749,887	$999,553

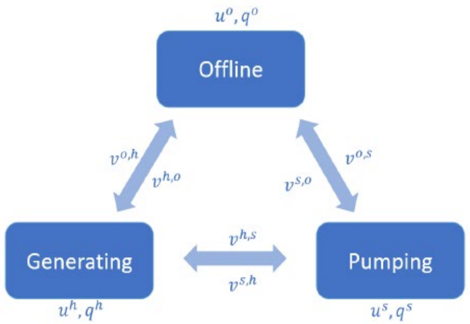
- The project spending was consistent with the project budget.

End-User Engagement and Dissemination

- Stakeholder and end-user engagement strategy
  - PSH owners, ISOs and broad stakeholder groups of electricity markets will benefit from reduced production costs of the system, increased profits of PSH owners, enhanced renewable energy utilization, and improved day-ahead and real-time price convergence.
  - MISO and three PSH owners in MISO were engaged. MISO was part of the research team, and PSH owners formed an industry advisory group that review research progress and provide feedback, data and operational insights in monthly review meetings.
- Project results dissemination
  - Research products have been disseminated through publications on peer-reviewed technical journals and presented at technical conferences (including FERC technical conference).
  - MISO considers incorporating the developed models into production in the future

Performance: Accomplishments For Day-ahead (Milestone 1.1)

- A prototype deterministic day-ahead (DA) security constrained unit commitment (SCUC) model with PSH optimization has been developed and implemented using HIPPO.
- It meets MISO's solution quality and performance requirement.
- Studies on actual MISO system showed 0.04%-0.67% reduction in system total cost and mostly positive with up to 97% increase in PSH profit.
- Proposed a "tighter" formulation of the state-of-charge constraints
  - have neutral or positive impact (e.g., up to 34% reduction in studied cases) on average computational time



Case	HIPPO	HIPPO + PSHU
#1	0.11 %	0.16 %
#2	325 sec	400 sec
#3	527 sec	391 sec
#4	519 sec	699 sec
#5	0.13%	0.67%
#6	144 sec	140 sec

	System Objective [$]	PSHU 1 Profit [$]	PSHU 2 Profit [$]	PSHU 3 Profit [$]
#1	0.4%	1%	10.8%	6%
#2	0.042%	0%	5.92%	−6.04%
#3	0.18%	0.57%	0%	NA
#4	0.188%	0.17%	97%	0.3%
#5	0.67%	2.45%	*	13%
#6	0.107%	0.84%	10.8%	NA

$$e_{r,t-1} + \sum_{g \in G_{psh,r}} q_{gt}^{pump} \eta_g^{pump} \leq \overline{E}, \forall r, \forall t \in [t_2, T]$$

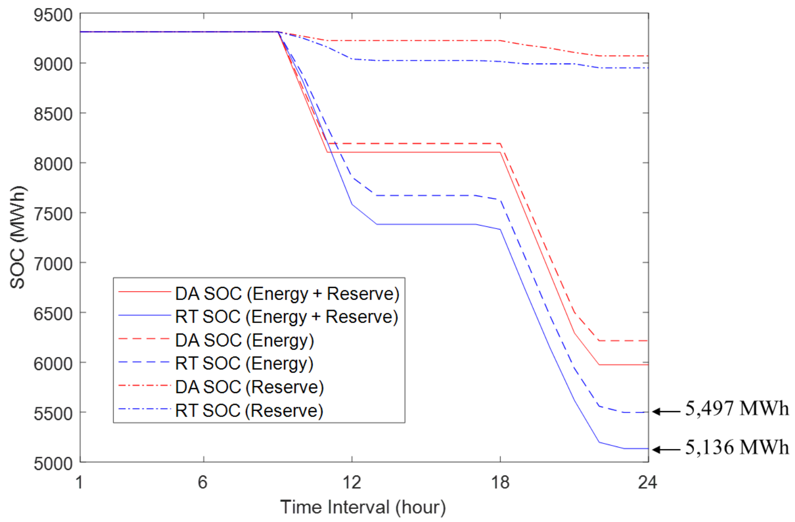
$$e_{r,t-1} - \sum_{g \in G_{psh,r}} \frac{q_{gt}^{gen}}{\eta_g^{gen}} \geq \underline{E}, \forall r, \forall t \in [t_2, T]$$

Performance: Accomplishments For Day-ahead (Milestone 4.1)

- An *energy reserve* (or *MWh reserve*) concept has been proposed to deal with the SOC deviation in real-time.
- Head room and floor room are derived using statistical models, based on MISO's historical data.

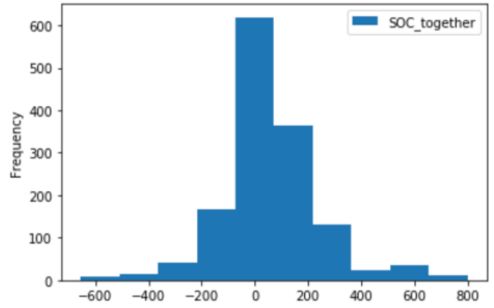
$$E^{LB} + \underbrace{E_t^{M+}}_{\text{Floor room}} \leq E_t \leq E^{UB} + \underbrace{E_t^{M-}}_{\text{Head room}}$$

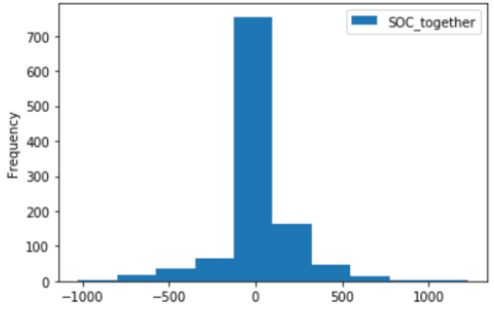
  - Numerical results show that the inclusion of energy reserve secure constraints can improve system security against uncertainties and contingencies, and meanwhile does not necessarily reduce profits of PSH units.




```
mean        60.333180
count     1414.000000
std        179.143915
Name: SOC_together, dtype: float64
------------------------------
mean                         60.3332
count                           1414
std                          179.144
ci95_hi     [411.4552528888061]
ci95_lo    [-290.7888926813568]
Name: SOC_together, dtype: object
```

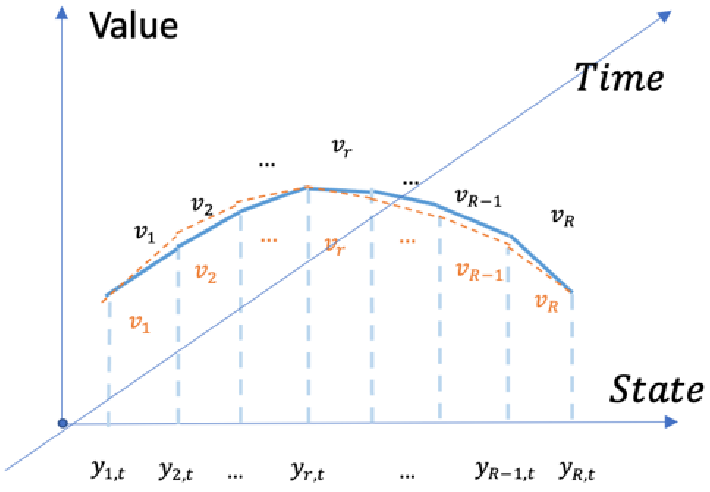
```
mean        14.436623
count     1102.000000
std        207.084638
Name: SOC_together, dtype: float64
------------------------------
mean                         14.4366
count                           1102
std                          207.085
ci95_hi     [420.3225135849308]
ci95_lo    [-391.4492679708957]
Name: SOC_together, dtype: object
```





Performance: Accomplishments For Day-ahead and Intra-day (Milestone 8.1)

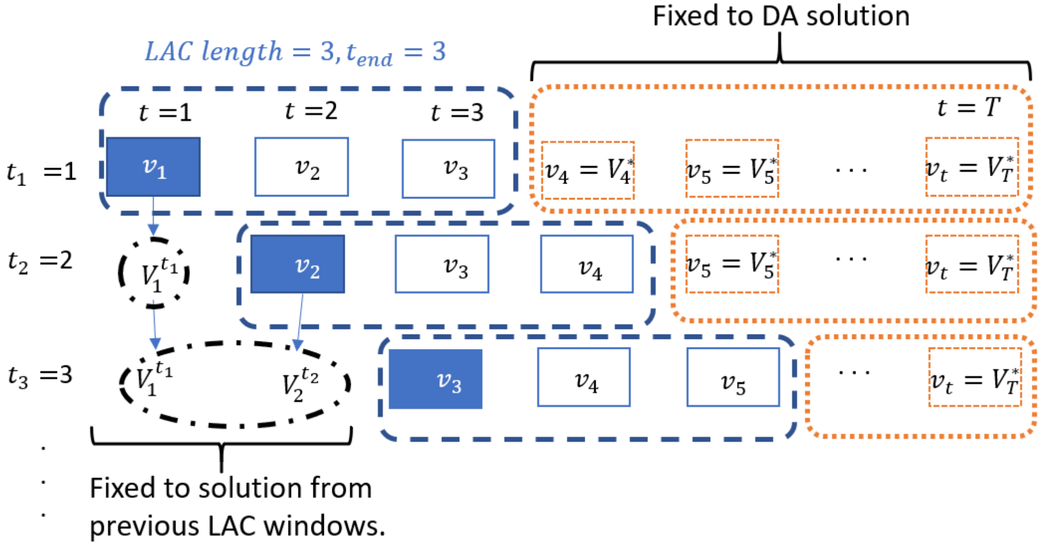
- Using MISO's historical data, we introduced new parameters to define scenarios describing DA to RT discrepancy.
- Used ADP to learn SOC-price curves for evaluating the value of water of PSHs outside a finite time horizon, which avoids the needs to explicitly simulate/forecast uncertainties of future time periods.
  - when the training set has more data, the ADP model becomes more robust and accurate.



Prediction	D1	D2	D3	D4
ADP	$15,661.79	$13,197.94	$6,827.14	$12,403.79
RT	$17,017.01	$16,270.65	$8,294.46	$18,734.72
Rolling	$11,334.57	$10,666.31	$6,784.00	$12,863.84
DA	$10,976.77	$9,026.81	$6,743.30	$10,198.84

Performance: Accomplishments For Intra-day (Milestone 2.1)

- A rolling window simulation platform has been developed in HIPPO, which closely mimics the look-ahead commitment (LAC) of MISO. It is a valuable tool for investigation of the intra-day clearing process.
  - HIPPO LAC simulation results have been validated to be consistent with DA solutions.

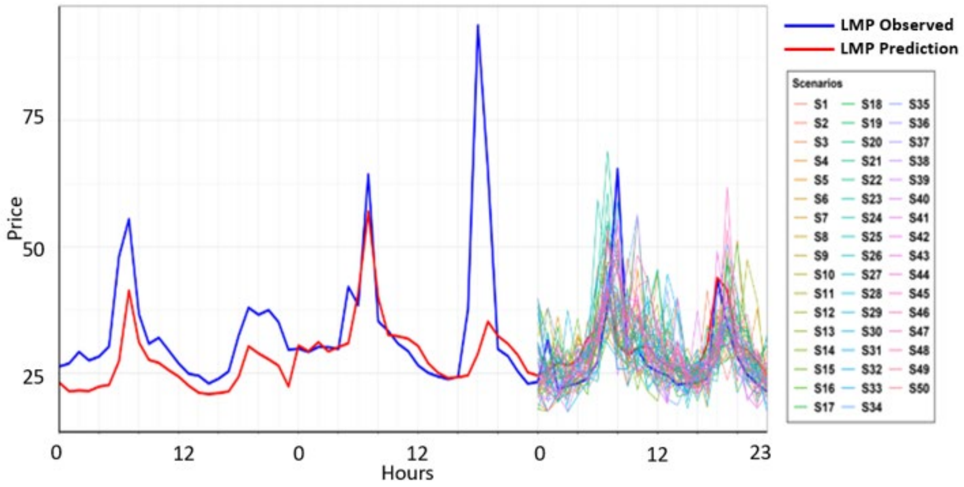


- A deterministic PSH optimization model is developed in the LAC formulation, which uses deterministic single point price forecast to guide SOC management.
  - An Autoregressive Integrated Moving Average with Exogenous Variable (ARIMAX) based forecast model has been developed for real-time (RT) LMP single point forecast.

$$Objective: Min \sum_{t=t_1}^{t_{end}} C_t(g_t, u_t) - \sum_{t=t_{end}+1}^{T} \sum_{g \in G_{psh}} LMP_{g,t}^{t_0}(q_{g,t}^{gen} - q_{g,t}^{pump})$$

Performance: Accomplishments For Intra-day (Milestone 5.1)

- A scenario generation-based stochastic price forecast have been developed to generate probabilistic RT price forecast.
  - The developed ARIMAX model can capture the trend, the peaks and the turning points of the actual RT-LMP significantly better than the Facebook Prophet model.



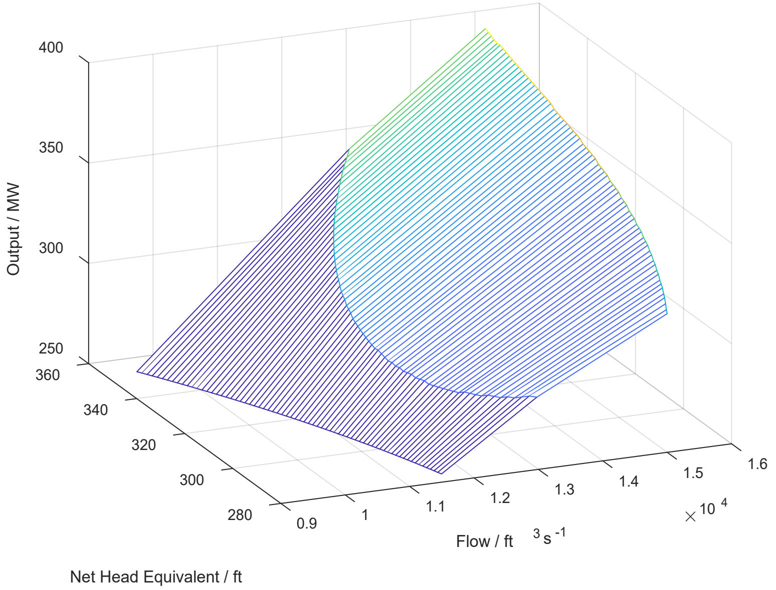
- A risk-averse formulation has been developed to address the concern of profit loss in the RT market.
  - Studies demonstrate the effect of the risk management formulation in reducing system total cost and avoiding negative real time profits for the PSHU.

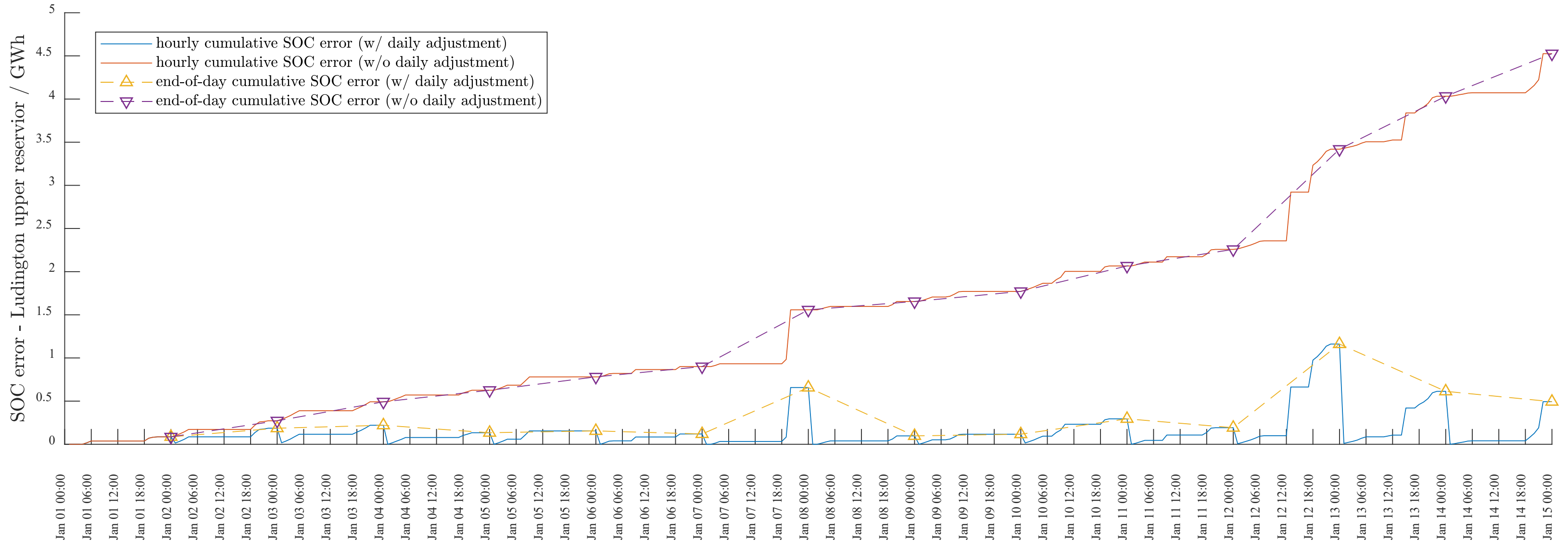
$$Objective: Min \sum_{t=t_1}^{t_{end}} C_t(g_t, u_t) + \sum_{r \in R} w_r$$

$$w_r \geq -\sum_{t=t_{end}+1}^{T} \sum_{g \in G_{psh,r}} LMP_{g,s,t}^{t_0}\left[\left(q_{g,s,t}^{gen} - q_{g,s,t}^{pump}\right) - \left(q_{g,t}^{gen,DA} - q_{g,t}^{pump,DA}\right)\right], \forall r \in R, \forall s \in [s_1, s_N].$$

Performance: Accomplishments For Planning (Milestone 3.1)

- A planning model with improved realistic characteristics of PSH has been developed.
  - Head dependent power bounds modeling, and Variable efficiency modeling
  - Studies using actual PSH plant parameters and MISO planning models reveal the SOC error from inaccurate PSH input-output curve modeling will accumulate quickly in chronological production cost simulation.
  - A novel disjunctive convex hull model for input-output curve approximation has been developed, which shows an order of magnitude speedup over the common piece-wise linear approximation methods





Performance: Accomplishments For Planning (Milestone 6.1)

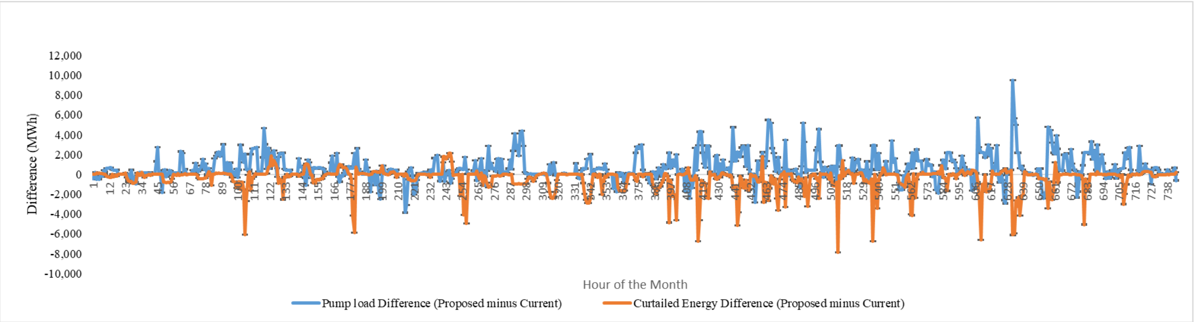
- Developed a planning model with market optimizations enhancements.
  - MWh reserve modeling was modeled in MISO planning cases using PLEXOS.
  - A value-of-water based approach was used for the RT operation of PSH units. The DA storage shadow price is used as estimated value of water.
  - Defining a value-of-water function for RT can enable the flexibility of PSH and reduce the overall system cost in the RT market (with a monthly average of 0.22% reduction in studied cases)

PSH RT operation strategy	January 2024 (10^3\$)	April 2024 (10^3\$)	July 2024 (10^3\$)	October 2024 (10^3\$)
Follows DA schedule	4,303,959	3,161,008	6,752,143	3,424,229
VOW	4,275,751	3,157,345	6,750,693	3,420,599
Cost Reduction (\$)	28,208	3,663	1,450	3,630
Cost Reduction (%)	0.66%	0.12%	0.02%	0.11%

Performance: Accomplishments For Planning (Deliverable 9.1)

- Explored a stochastic optimization approach for economic planning studies
  - A linear program based approximated model is first used to approximate the nonconvex unit commitment model to accelerate the solution of stochastic production cost simulation models.
  - Explored a stochastic transmission expansion planning method with the linear approximation method and a decomposition framework.
- Long-term production cost simulation was performed on MISO planning cases.
  - Results show enhanced PSH optimization can reduce renewable curtailment and load cost, and in some cases increase CO_2 emission.

	Objective Value ($\$10^8$)			CPU time (sec)		
	MILP UC	LP approx.	Difference in Percentage	MILP UC	LP approx.	Time Reduction in Percentage
Stochastic production cost simulation	8.935	8.904	0.35%	17174 (or 4.771 hours)	4873 (or 1.354 hours)	71.6%



Q&A