Optimizing Hydroelectric Pumped Storage in PJM's Day-Ahead Energy Market

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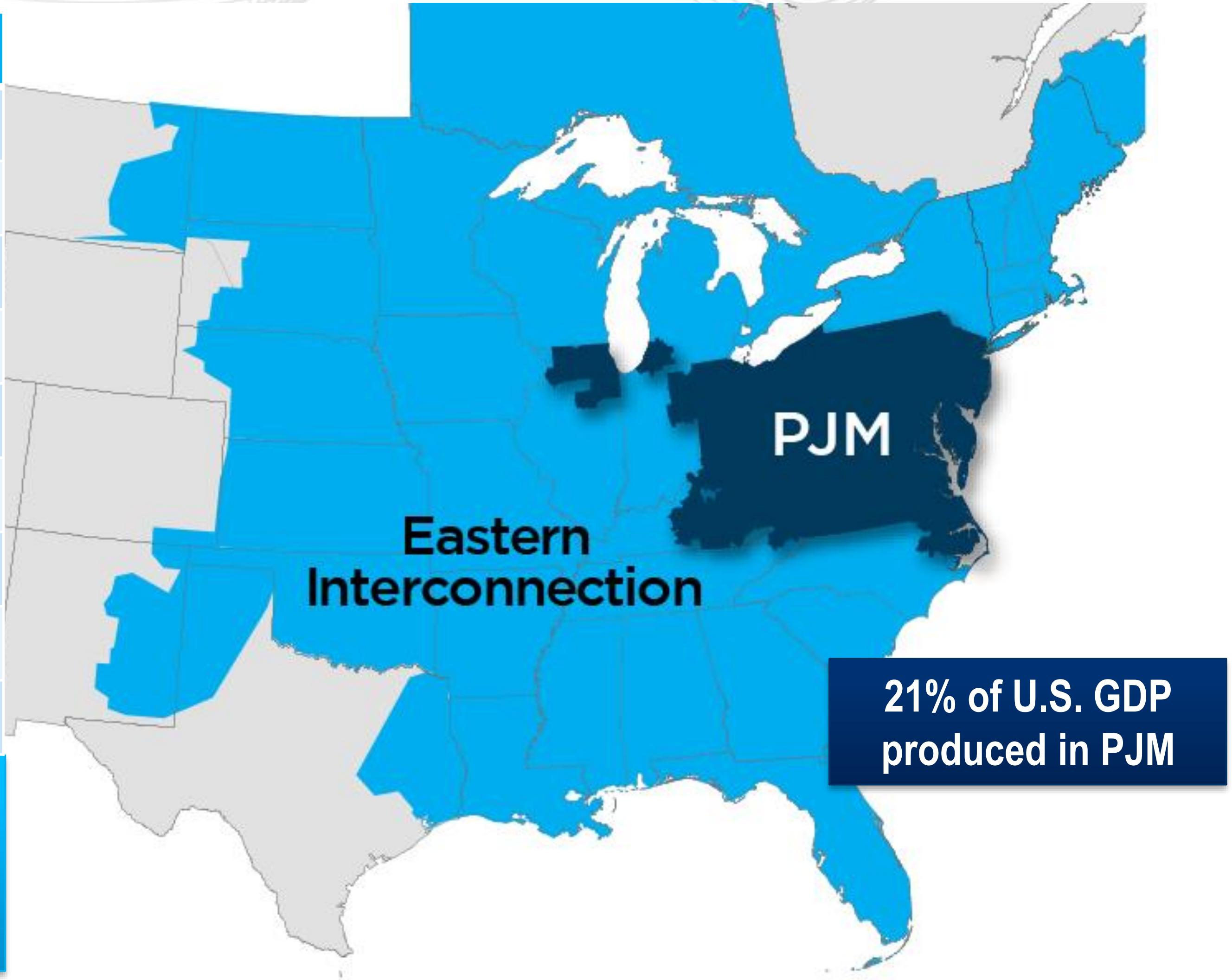
FERC Technical Conference
June 23, 2020

PJM as Part of the Eastern Interconnection

Key Statistics	
Member companies	1,040+
Millions of people served	65
Peak load in megawatts	165,563
MW of generating capacity	186,788
Miles of transmission lines	84,236
2019 GWh of annual energy	787,307
Generation sources	1,446
Square miles of territory	369,089
States served	13 + DC

- 27% of generation in Eastern Interconnection
- 26% of load in Eastern Interconnection
- 20% of transmission assets in Eastern Interconnection



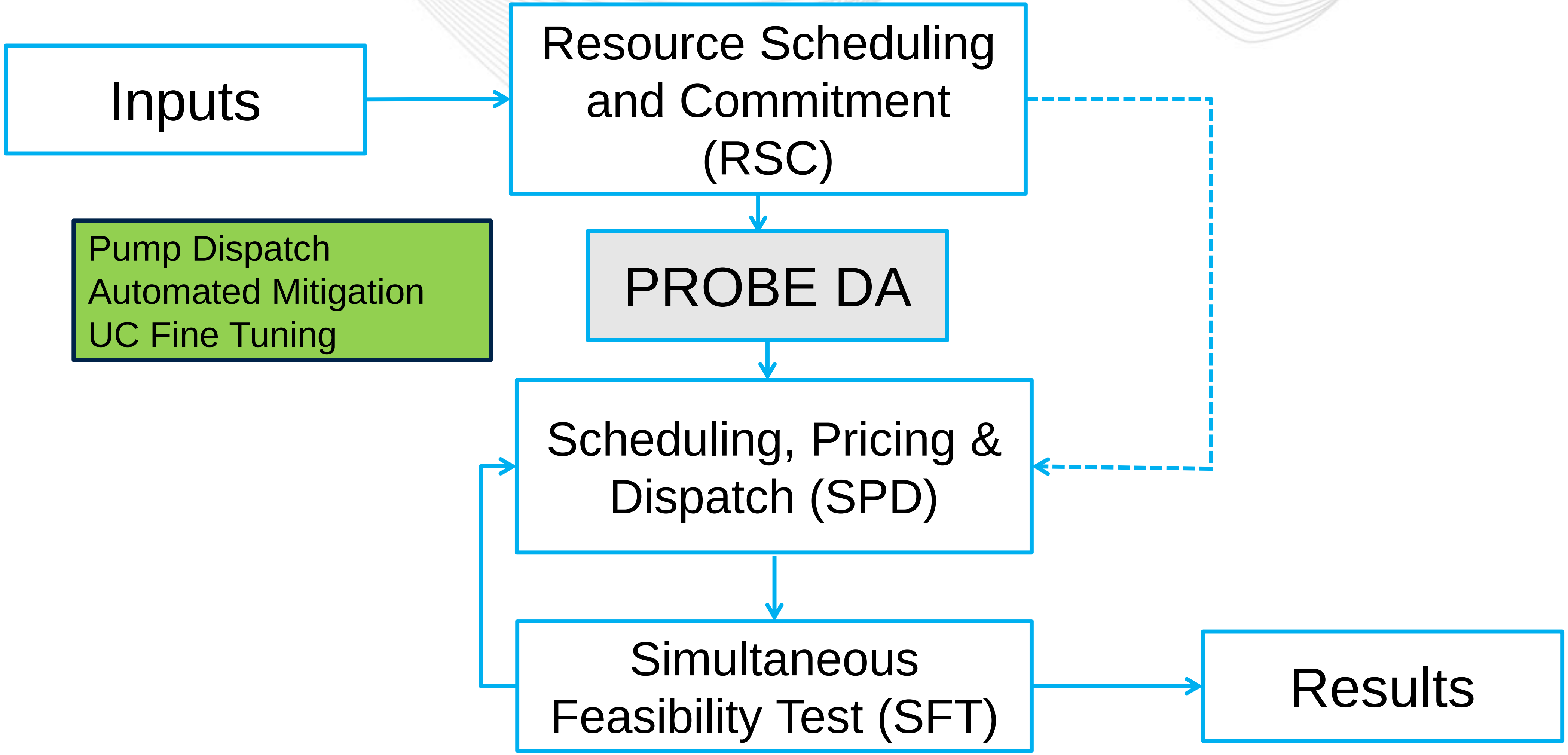
As of 1/2019

Agenda

- PJM Day-Ahead Market Clearing
- PJM Pumped Hydro Optimizer
  - Model
  - Solution Algorithm Evolution
- Pumped Hydro Optimizer Challenges and Recent Developments
  - Current Challenges and Opportunities
  - Recent Enhancements
- Questions

PJM Day-Ahead Market Clearing

Day-Ahead Market Clearing Process



Use of PROBE DA in Day-Ahead Market Clearing

- Provides unit commitment suggestions to aid Day-Ahead Market Operators
- Performs a Three Pivotal Supplier (TPS) test for market power mitigation
- Optimizes hydro pumped storage schedules
- High performance SCUC engine
  - Does not use third party solvers
  - Typically 3-7 minutes to solve
- Considers:
  - All N-1 constraints, thousands of monitored branches and contingencies
  - Network and Market-to-Market flowgates
  - Iterative load flow with marginal losses updates
  - Ancillary services – system-wide and zonal
  - PAR optimization
  - All DA unit parameters
  - Submitted transactions
  - Virtual bids including large volumes of up-to-congestion (UTC) transactions
  - DFAX computed on the fly

Pumped Hydro Treatment in Day-Ahead and Real-Time Markets

- Day-Ahead:
  - Either self-scheduled or scheduled via pumped hydro optimizer (no offers)
  - Eligible for reserves when pumping via curtailment

- Real-Time:
  - Units can “self-schedule” deviations from day-ahead commitment schedule (PJM requires 20 minutes notice and assess deviation charges)
  - PJM can manually dispatch changes in schedule (no deviation charges)
  - Pumped hydro is absent from intraday commitment engines and RTSCED except to the extent the schedule is an input

PJM Pumped Hydro Optimizer

Pumped Hydro in PJM

- 5 Pumped Hydro Plants in PJM
  - Over 5,500 MW of generating capacity

- Pumped Hydro Optimized in DA only
  - Optimized over 24 hours
  - Objective is to maximize total social welfare
  - Optimize energy and ancillary service hourly dispatch
  - Guarantee profitable - protects owners from losing money when LMP deviates from forecasted

3,003 MW Bath Country Pumped Hydro, built in 1985 in Virginia

Pumped Hydro Model Parameters

- Pump Efficiency Factor (typically in 0.7-0.85 range)
  - 0.8 means that 20% of energy stored during pumping will be lost
  - Most important bid-in parameter
- Initial Reservoir Level (amount of energy available in MWh before hour ending 1)
- Final Reservoir Level (amount of energy in MWh at end of day)
- Maximum and Minimum Reservoir Level (MWh)
- Maximum and Minimum Generation and Pumping (MW)

1,070 MW Muddy Run, built in 1968 in Lancaster County, PA

Role of Pumped Hydro in Ancillary Services

- Pumped hydro plays a major role in ancillary services due to its high ramp rate and large capacity.

- In the PJM Day-Ahead Market, pumped hydro units are eligible to provide 30-minute day-ahead scheduling reserve (DASR). Offer MW is dependent on the unit's status:

Pumping Mode	Min(Pump MW, ramp_rate*30)
Offline	Min(EcoMax, ramp_rate*30)
Generating Mode	Min(EcoMax – Gen MW, ramp_rate*30)

- PROBE DA co-optimizes energy and ancillary services. It will automatically consider each unit's opportunity cost when determining a unit's energy vs. ancillary services MW output.

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Evolution of Pump Hydro Optimization Solver

- ‘05 — PROBE Day Ahead
- ‘06 — Global Pumped Hydro Optimizer
- ‘15 — Sequential Pumped Hydro Optimizer
- ‘16-18 — Pump Blocking Fine Tuning
- ‘19 — R&D on applying Pump Lite Model for ESRs
- ‘19-20 — Deal With More Inflexible Pump Ranges
- ‘20 — Pro-active Pump Iteration Step Control

Method 1 – Global Single SCED

- Global multi-period single SCED (GSS) approach solving 24 hours at once
  - Objective function is the same as usual – maximize system total social welfare

- Pump constraints added explicitly
  - Reservoir limits, end of the day SOC, etc.

- GSS method produced the “global” optimal solution
  - Achieved the highest possible total social welfare
  - Allowed pump hydro units to set price

Method 1 – Global Single SCED

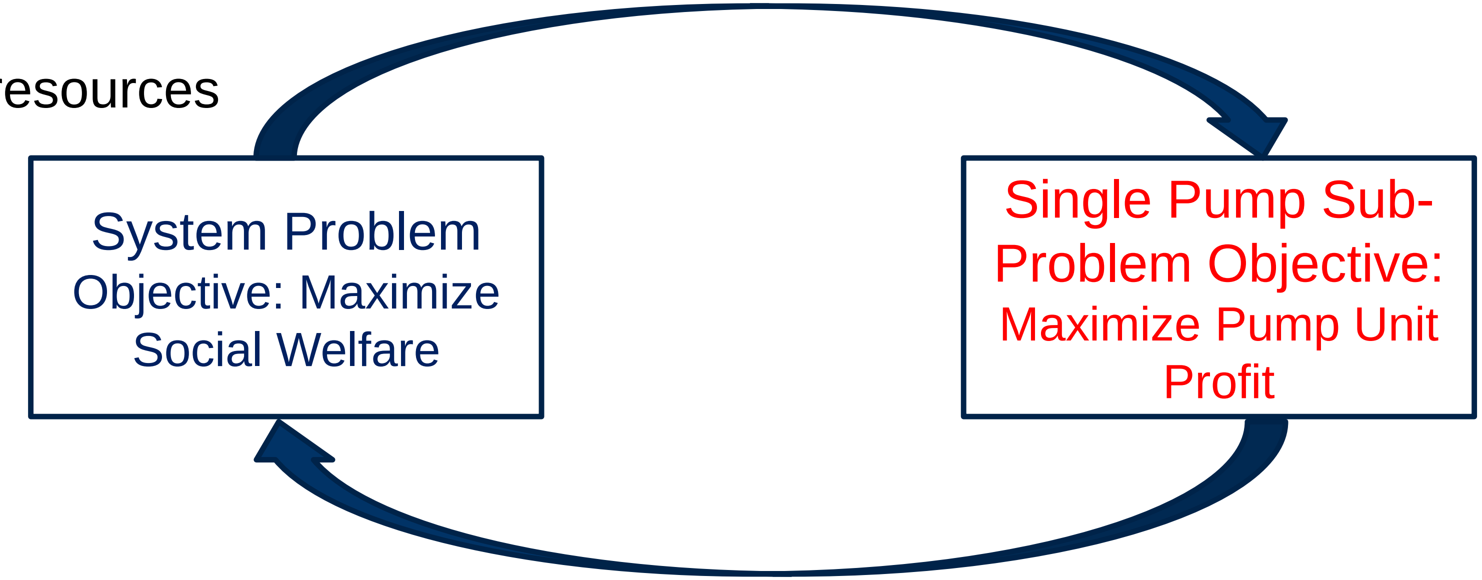
- Resulted in huge SCED size
  - 24 times more optimized energy bids, including generator energy/ASM bids, virtual bids and UTC bids (if 25,000 controls per hour, then SCED has 600,000 controls per day)
  - More binding constraints
    - 24 times more energy balance, transmission and ancillary service generator maximum constraints
    - Generator ramping limit constraints were also added

- Performance was an issue
  - Most cases solve in 10-25 minutes, but tough cases would take more than an hour
  - 5,000+ binding constraints
  - Expanding ancillary services and increase in virtual bids had major performance impact

- Final pricing run was still using sequential LP

Method 2 – Sequential Iterative SCED

- Sequential Iterative SCED (SIS) method was developed to use decomposition techniques to speed up the pumped hydro optimization
  - 5-7 times faster than the GSS method
  - Better improvement seen on tougher days
  - Room to add more advanced features
    - Sub-hourly time step
    - More energy storage resources



Method 2 – Sequential Iterative SCED (SIS)

System LP Problem

- Solve the system SCED sequentially for each hour
- Maximize total social welfare
- Assume pumped hydro injections are fixed
- Produce LMPs at each pumped hydro location

Local Pump LP and UC

- Solve the 24-hour pumped hydro dispatch problem one unit at a time
- Maximize the study pump unit's daily profit
- Assume LMPs at terminal buses are fixed
- Enforce pumped hydro model parameters (capacity limits, SOC, etc.)
- Enforce minimum down time between pumping and generating

Sequential Iterative SCED – Solution

- Convergence of the System and Local Pump LPs isn't guaranteed but requires carefully designed de-oscillation convergence mechanism
  - Limit the maximum unit MW change per hour in one iteration
  - Maximum unit MW change will be reduced if:
    - Unit MW change results in too significant an LMP change
    - Anticipated cost savings from the Local Pump LP can't be realized in the System LP
  - The iterations stop once anticipated cost savings is lower than a threshold
  - Many "small" iterative steps are needed to get to a converged solution

- Pump UC is needed to enforce minimum up/down time

Enforcement of Minimum Generator and Pump Constraints – Pump Blocking

- Pumped hydro are often not very flexible, especially in pumping mode

- Enforcing minimum generator and pump constraints can be challenging
  - Large change in LMPs in presence of congestion – common due to the large size and location of units
  - May conflict with other physical parameters, such as SOC limits

- PROBE DA solution:
  - Delay enforcing minimum generator/pump constraints until later in the solution
  - At the end, perform "Pump Blocking" – gradually move into feasible range (either to gen/pump minimum or to 0 MW) and resolve LP after each step due to SOC
  - May conflict with end of day SOC – difficult to automate

Pump Blocking Step Example

- Determining blocking direction (to 0 MW or the gen/pump minimum) generally depends on the relative closeness to 0 MW or gen/pump minimum
- Also need to take into consideration the possibility of another resulting violation
- Impact will propagate to other hours and units so pump blocking is carried out one unit one hour at a time
- Pump blocking is more difficult for units with large dispatchable range gaps

HH:MM	LMP	Dispatch	ResrLevel	LMPIdeal	DispIdeal	ResrLevel	PumpMax	PumpMin	GenMin	GenMax
00:00	15.24	0	8330	15.24	0	8330	-696	-696	170	790
01:00	14.5	0	8836.4	14.5	**-633**	8836.4	-696	-696	170	790
02:00	14.25	-696	9393.2	14.25	-696	9393.2	-696	-696	170	790
03:00	14.33	-696	9950	14.33	-696	9950	-696	-696	170	790
04:00	14.8	0	9950	14.8	0	9950	-696	-696	170	790

Has to be blocked to 0 MW instead of -696 MW

Ideal dispatch relaxes minimum generator/pump constraints

Due to reaching the Maximum Reservoir level 9,950 MWh in a later hour

Pumped Hydro Optimizer Challenges and Recent Developments

Pumped Hydro Optimizer Challenges and Opportunities

1) Better handle inflexible pumped hydro resources
2) Gracefully handle conflicting bid-in pump requirements
3) Further improve pumped hydro optimizer speed to manage the increased number of pumped hydro resources
4) Prepare for the potential use of the pumped hydro optimizer for other types of storage resources
5) Allow unit owners to bid in cost curves with a range of final SOC levels
6) Let pumped hydro units set the price (units cannot directly set price now but can greatly influence pricing)
7) Could/should pumped hydro SOC be optimized after the Day-Ahead Market?

Recent Enhancements – Challenge #1 & #2
Soft/Progressive Enforcement of Pump Constraints (SEPC)

- Units may bid in conflicting operating constraints leading to infeasible conditions
  - For example:
    - The limited dispatchable range of a unit may prevent it from reaching the desired end of day SOC
    - As Local Pump LP iteration progresses, it may temporarily get into an infeasible condition during the limitation of the unit MW change or pump blocking
  - Under these cases, PJM wants PROBE DA to gracefully reach a solution that provides the best possible result; if constraints have to be violated, the preferred sequence is:
    - SOC limit > Range limit > Reservoir limit

- Soft/progressive enforcement of pump constraints:
  - Provide multi-segment constraint penalty curves that allow small temporary violations
  - Progressively enforce harder penalties as the solution is reached
  - Support the preferred violation sequence

SEPC – Example

- SEPC is applied to monitoring LP Variables (such as SOC) to improve convergence
- SEPC also helps deal with inflexible pumping range issues
- Using end of the day SOC limit as an example – assume the desirable end of day SOC limit is 4,104 MWh.

Without SEPC

Segment	From MWh	To MWh	Slope ($)
1	-9999	4103.99	-1,999.00
2	4103.99	4104.01	0.00
3	4104.01	9999	1,999.00

Hard enforcement of the constraint limit.

With SEPC

Segment	From MWh	To MWh	Slope ($)
1	-9,999.00	3,704.00	-1,999.00
2	3,704.00	4,103.99	-200.00
3	4,103.99	4,104.01	0.00
4	4,104.01	4,504.00	200.00
3	4,504.00	9,999.00	1,999.00

The slope may progressively increase as the solution approaches the limit.

SEPC – Test Results

- PJM has experienced difficulty obtaining solutions due to units with limited pump side dispatchable ranges
  - Minimum pump range was violated in some cases
  - Generating at wrong hour (price too low to generate) in other cases

- After SEPC was implemented
  - Solution problems were resolved
  - Achieved significant speed improvements

	Solution Time (seconds)		
Test Day	With SEPC	Without SEPC	**Change in Solution Time**
Day 1	64	59	**8%**
Day 2	70	105	**-33%**
Day 3	83	102	**-19%**
Day 4	87	109	**-20%**
Day 5	137	165	**-17%**

Recent Enhancements – Challenge #3 & #4
Pro-active Pump Iteration Step Management

- Currently, the pump iteration step adjustment is reactive.
  - When solving the Local Pump LP, PROBE assumes that the external LMP is fixed.
  - Will only reduce max. unit MW change after finding that LMP has changed too much in the System LP (has to reject solution and resolve with reduced step size).
  - Trial-and-error approach may not be efficient because the redispatch of one hour will impact other hours.
- If when solving Local Pump LP we can accurately predict how the external LMP will react to a varying range of MW injections, we can establish an injection cost curve for the pump controls for the Local Pump LP.
- More elastic control dispatch range will also help with Pump Blocking
- Challenge is to be able to efficiently compute the external LMP response curve

- PJM has been optimizing the schedules of its pumped hydro storage units since 2006
- Pumped hydro optimization algorithm has been continuously evolving to meet the market’s changing needs
- Storage optimization of pumped hydro units is computationally intensive
  - With renewable growth it is anticipated there will be a rapid increase of energy storage resources (ESRs)
  - Enhancements are under development to improve the solution and performance