Reliable, Efficient and Incentive-compatible Solutions for Operating Energy Storage in ISO/RTO Markets

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Agenda

- State-of-the-art in scheduling and pricing of energy storage resources (ESR)
- NOPR on Energy Storage & DER and scheduling/pricing challenges and R&D
- Scheduling and pricing ESR in day-ahead markets
- Scheduling and pricing ESR in real-time markets

Energy storage State-of-the-art

- Most areas have rules for allowing limited energy storage resources participating in regulation markets
- Most areas with pumped storage have ways that pumped storage can participate in energy, ancillary, and capacity markets
  - Bid as a load resource to provide energy and non-spin reserve as a pump
  - Bid as a generator (similar to thermal plant) to provide energy, regulation, spin as a generator
  - Typically cannot bid as both in same hour
- Some areas have or are proposing/developing storage optimization models for pumped storage
  - PJM hydro optimizer, ISO-NE DARD pump
- Discussion around the following (including FERC NOPR RM16-23)
  - Are the current/evolving scheduling procedures for pumped storage sufficient for pumped storage
  - Can the advanced pumped storage models be applied/adapted to limited energy storage (batteries), and if so what changes are required
  - When is ISO management of SOC warranted
  - How can limited energy storage participate in other markets beyond regulation

Energy Storage and DER Participation (storage focus)

FERC NOPR Summary

- Energy storage to be allowed to participate in energy, ancillary services, and capacity markets when technically able
  - Create participation model to do this
  - Allow for provision of non-market (e.g., cost-based) services that they are capable of providing as well
- Specific allowance requirements:
  - Propose provision of spinning/synchronous reserve even though they are not “synchronous”
  - Propose participation in capacity market by prorating max discharge capacity by ratio of storage energy limit over minimum capacity market duration requirement
- Certain bidding requirements for energy storage
  - State of charge, upper/lower charge limits, charge/discharge rates
  - Additional optional parameters
  - No requirement for the ISO to manage the state of charge of ESR
- Participate as wholesale buyer and seller – energy it charges to sell later must be at wholesale
- Minimum size no greater than 0.1MW
- Set price as both a buyer and seller

Comparison of large (pumped storage) vs limited storage (batteries)

	Pumped storage	Batteries/limited energy device
Power capacity (size)	Hundreds of MW per each unit (2-6 units per plant)	Typically 20 MW or less (some larger exist)
Minimum capacity	Minimum generation ~40% Minimum pumping ~100%	Continuous operation between max charge and max discharge
Energy/reservoir limits	Several hours to days (SOC for regulation control irrelevant)	Typically < 4 hours, often < 1 hour
Flexibility and speed	Fairly fast in generating mode, non-dispatchable in charging mode	Very fast throughout operating range
Transitions	Transition times of 15-30 minutes between gen and pumping modes (DAM may require full hour between transition)	No transition time, continuous operation
Round-trip efficiency	Typically ~80%	85%-95%

Additional bidding information for pumped storage units

- Maximum daily energy consumption (MISO, ISO-NE)
- Ending reservoir level (PJM)
- Maximum number of daily starts
- Round-trip efficiency
  - Variable efficiency levels typically require additional integer variables
- Min/Max Reservoir limits (PJM)
- Minimum pumping capacity limits
  - Most PSH fixed speed pump technology and not adjustable-speed
- Cycle limits (NYISO proposal)
- Ending reservoir value ($/MWh stored at end of period) (not used yet)
- Pump shut-down cost (CAISO)
- Minimum pumping time
- Transition times (CAISO)

Selected Research Topics

- Bidding and scheduling of ESR in day-ahead (long-horizon, hourly SCUC) energy markets
- Bidding and scheduling of ESR in real-time (single- or limited time-horizon, sub-hourly SCUC & SCED) energy markets
- Self management vs. ISO optimized – efficiency and reliability impacts
- Price formation topics with ESR as marginal resources – how/when ESR can set price
- Provision of A/S, co-optimization of energy and A/S for ESR considering energy limits and characteristics of ESR
- AGC enhancements for extracting max value out of ESR
- Settlement design (including make-whole payments)
- Small resource impact and computational impacts of significant ESR numbers
- Treating ESR in capacity markets

Day-ahead scheduling designs (self management of SOC limits)

- Energy storage resources simply bid as two resources, demand and generation, with decremental/incremental offer curves
  - Simple logic prevents SCUC from choosing both in same hour (similar to logic that prevents multiple configurations of a combined cycle)
- Single incremental energy offer curve which can range from negative Pmin to positive Pmax with negative to positive incremental energy costs
  - CAISO NGR model
- Must allow hourly Pmax/Pmin and hourly offer curves

Day-ahead scheduling designs (ISO optimization of SOC limits)

- Beginning SOC (based on previous day's DAM) and offered end-of-day SOC, max/min SOC limits, and round-trip efficiency ratio
  - ISO meets SOC constraints to reduce overall production costs
  - Question of how well this works for LESR
  - Allow for additional SOC set points throughout the day
- Same as above, rather than end-of-day SOC, ESR offers a SOC "leftover value". This is $/MWh offer based on amount left at end of day.
  - May give more flexibility for using ESR more/less when the costs for the day are higher/lower than originally anticipated
  - Requires ESR to estimate the overall value of its energy the following day.
  - 2-day SCUC may help as well
- Spread bids - $/MWh required to operate for the day (e.g., to cover O&M costs)
  - May be challenging given imperfect alignment of costs and prices
  - Similarly, offer-based penalties from straying from end-of-day SOC (above designs combined)
- PSH and CAES likely need commitment constraints and rough zones, batteries and flywheels do not

SOC Management

- ISO optimization of SOC and assurance of schedules within SOC limits leads to following pros/cons
  - Improved reliability through assurance of supply
  - Economic efficiency improvements through optimized solution
  - Theoretically, though not proven, increased profits for storage
  - Increased complexity and computation, challenge for market clearing
  - Less explicit flexibility from participants (though SOC optimization likely to be option and not required)
- RUC option
  - ESR offer separately in DAM with bids/offers for injector/withdrawer options
  - ISO then ensures that ESR selected schedule does not violate SOC limits – or whether enough resources committed if it does
  - May be necessary at high ESR penetrations

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Comparison of Day-ahead options

End of Horizon SOC Level Offer

+ SoC for next day's anticipated utilization is ensured
+ Setting SoC level for end of day is straightforward
– LMP not set directly by ESR
– If higher priced day than anticipated, ESR cannot take advantage

End Of Horizon SOC Value Offer

+ Prices are set at level determined by ESR owner
+ If prices higher than anticipated, ESR and system can use more energy, and vice-versa
– Could potentially run lower on SoC at end of day than planned
– ESR must determine what the somewhat arbitrary value of SoC left is

ESR Day-ahead modeling

$$S_{i,t} = S_{i,t-1} + \eta_i^c P_{i,t}^c - \eta_i^D P_{i,t}^D \;\; \forall t$$

$$\underline{S_{i,t}} \leq S_{i,t} \leq \overline{S_{i,t}}$$

End Of Horizon Constraint

$$S_{i,24} = \hat{S}_i$$

End Of Horizon Value

$$minimize \sum F_i * P_{i,t}^D \; - S_{i,24} * SV_i$$

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Marginal Cost Pricing

$$\mathcal{L} = \{\sum F_i * P_{i,t}^D - \lambda_t \sum (P_{i,t}^D - P_{i,t}^C) - DMND_t$$

$$- \sum \overline{\mu_{i,t}^D}\,(\overline{P_i^D} - P_{i,t}^D) + \sum \underline{\mu_{i,t}^D}\,(P_{i,t}^D - \underline{P_{i,t}^D})$$

$$- \sum \overline{\mu_{i,t}^C}\,(\overline{P_i^C} - P_{i,t}^C) + \sum \underline{\mu_{i,t}^C}\,(P_{i,t}^C - \underline{P_{i,t}^C})$$

$$- \sum \gamma_{i,t}(S_{i,t} - (S_{i,t-1} + \eta_i^C P_{i,t}^C - \eta_i^D P_{i,t}^D))$$

$$- \overline{\xi_t}(\overline{S_{i,t}} - S_{i,t}) - \underline{\xi_t}\left(S_{i,t} - \underline{S_{i,t}}\right)\} + \chi\left(S_{i,24} - \hat{S}_i\right)$$

$$\frac{\partial \mathcal{L}}{\partial P_{i,t}^D} = F_i - \lambda_t - \overline{\mu_{i,t}^D} + \underline{\mu_{i,t}^D} - \gamma_{i,t}\eta_i^D = 0$$

$$\lambda_t = F_i - \overline{\mu_{i,t}^D} + \underline{\mu_{i,t}^D} - \gamma_{i,t}\eta_i^D$$

$$\gamma_{i,t} - \gamma_{i,t+1} + \overline{\xi_t} + \underline{\xi_t} = 0$$

$\gamma_{i,24} = \chi$ or $\gamma_{i,24} = SV_i$

If ESR not at charge/discharge max/min, LMP equal to shadow price of SoC constraint

Shadow price of SoC constraint equals the End-of-Horizon SoC constraint unless SoC limits are binding

SoC EoH Constraint vs. SoC EoH Value sets the value at end of day

Dual solution must be solved for entire horizon, not interval by interval

Pricing Calculation SoC Constraint

LESR, -100 to 100, 50MWh SoC max,

Final SoC @ 25Mwh

$$\gamma_{i,t} = \gamma_{i,t+1} - \overline{\xi_t} - \underline{\xi_t}$$

Hour	Schedule	SoC	LMP	γ	ξmin	ξmax
1	23	25	26.66	-26.6624		
2	2	2	23.32	-26.6624		
3	0	0	20.65	-26.6624	7.658	
4	0	0	20.65	-19.0046		
5	0	0	20.65	-19.0046		
6	-2	0	19.54	-19.0046		
7	-46.5051	1.98	18.81	-19.0046		
8	-2	48.02	19.83	-19.0046		
9	0	50	23.32	-19.0046		-15.871
10	0	50	24.47	-34.8761		
11	0	50	23.32	-34.8761		
12	0	50	24.47	-34.8761		
13	0	50	23.32	-34.8761		
14	0	50	23.32	-34.8761		
15	0	50	23.32	-34.8761		
16	0	50	23.32	-34.8761		
17	0	50	26.66	-34.8761		
18	2	50	34.88	-34.8761		
19	46	48	34.88	-34.8761		
20	2	2	34.88	-34.8761		
21	0	0	28.14	-34.8761	14.845	
22	0	0	26.66	-20.0317		
23	-2	0	23.32	-20.0317		
24	-23.2525	1.98	19.83	-20.0317		
End of day		25		-20.0317		

Pricing Calculation SoC Value

LESR, -100-2 to 2-100, 50MWh SoC max,

$$\gamma_{i,t} = \gamma_{i,t+1} - \overline{\xi_t} - \underline{\xi_t}$$

SoC Value @$20/Mwh

Hour	Schedule	SoC	LMP	g	ξmin	ξmax
1	23	25	28.14	-28.1393		
2	2	2	26.66	-28.1393		
3	0	0	21.07	-28.1393	9.135	
4	0	0	23.32	-19.0046		
5	0	0	23.32	-19.0046		
6	-2	0	19.83	-19.0046		
7	-46.5051	1.98	18.81	-19.0046		
8	-2	48.02	19.83	-19.0046		
9	0	50	23.32	-19.0046		
10	0	50	24.47	-24.4715		-5.47
11	11.62706	50	24.47	-24.4715		
12	2	38.37294	24.47	-24.4715		
13	-11.7647	36.37294	23.32	-24.4715		
14	-2	48.02	21.07	-24.4715		
15	0	50	23.32	-24.4715		
16	0	50	23.32	-34.8761		-10.40
17	0	50	26.66	-34.8761		
18	48	50	34.88	-34.8761		
19	2	2	34.88	-34.8761		
20	0	0	34.88	-34.8761	14.876	
21	0	0	28.14	-20		
22	0	0	26.66	-20		
23	0	0	23.32	-20		
24	0	0	19.83	-20		
End of day		25		-20		

Pricing Calculation SoC Value PSH

PSH, -100 to 40-100, 800MWh SoC max,

SoC Value @$25/Mwh

$$\gamma_{i,t} = \gamma_{i,t+1} - \overline{\xi_t} - \underline{\xi_t}$$

Hour	Schedule	SoC	LMP	g	ξmin	ξmax
1	50.00159	400	25	-25		
2	40	349.9984	21.06802	-25		
3	0	309.9984	21.06802	-25		
4	-100	309.9984	23.32332	-25		
5	-100	394.9984	23.32332	-25		
6	-100	479.9984	19.83134	-25		
7	-100	564.9984	18.81451	-25		
8	-100	649.9984	19.83134	-25		
9	0	734.9984	20.64945	-25		
10	0	734.9984	21.06802	-25		
11	0	734.9984	23.32332	-25		
12	0	734.9984	24.47155	-25		
13	0	734.9984	23.32332	-25		
14	0	734.9984	23.32332	-25		
15	0	734.9984	23.32332	-25		
16	0	734.9984	23.32332	-25		
17	100	734.9984	26.66244	-25		
18	100	634.9984	34.87614	-25		
19	100	534.9984	34.87614	-25		
20	100	434.9984	34.87614	-25		
21	100	334.9984	26.66244	-25		
22	40	234.9984	26.66244	-25		
23	0	194.9984	23.32332	-25		
24	-100	194.9984	20.64945	-25		
End of day		280		-25		

Notable Day-ahead Questions

- What is the probability that self-management of SoC in day-ahead market will lead to infeasible schedule?
- Do reserve requirements require explicit energy-based duration constraints?
  - If they do, how often will LESR be selected for energy vs. reserve?
- Could ESR learn SoC constraints or SoC value strategies in day-ahead market to be efficient?
- In perfect real-time conditions, could LESR day-ahead schedules match real-time schedules?
- Can lost opportunity costs move across intervals?

Real-time market – Differences from Day-ahead

- Better forecasts of actual conditions in real-time can make adjustments from the day-ahead schedule beneficial for the ESR resource (prices) as well as the ISO (reliability and efficiency)
  - In order for ESR to be a true enabler of VER, it must change output to accommodate VER forecast error
- If optimized in the day-ahead, adjusting in real-time can impact later hours not part of the real-time optimization
  - Solution comparison: “Better information, but less of it”
- Sub-hourly resolution: Take advantage of limited energy storage resources to fill gaps that they could not in hourly resolution
- Fewer commitments mean more options for storage to meet deficiencies

Real-time Market Example

- ESR given a 24-hour day-ahead schedule such that it optimized to reduce total costs for the day and had ending SOC based on offered amount
  - 10:00-11:00 DAM schedule 100 MWh, DAM LMP $30/MWh
  - Pmax 200MW, Pmin -200MW, SOCMin 0 MWh, SOCMax 800MWh
  - Hour 16:00 it hits its SOC max of 800 MWh, pricing during hour 16:00 is $60/MWh
- RTM optimizes over 1-hour horizon at 5-min intervals
  - RTM LMP for 10:00-10:05 $50/MWh, with prices higher than $30/MWh for entire hour
  - Should the ESR move up above 100 MW?
  - In order to achieve same end of day SOC, will have to reduce output during future hour
  - In order to maintain SOC limit, will have to reduce output before 15:00

Order 825 Implications

Hub	Mean	Hourly LMP Standard Deviation	5-min LMP Standard Deviation
NP15	44.78138	31.49648	47.28198
SP15	44.1414	35.13636	52.90619
ZP26	42.49962	31.80989	47.42225
NP15	32.595	37.86295	56.55957
SP15	30.22986	43.27024	63.74167
ZP26	29.19416	38.93908	57.1989
NP15	28.72327	40.75771	64.84319
SP15	28.16812	44.79052	69.74059
ZP26	27.0257	39.86507	63.06573

Real-time market energy arbitrage opportunities with FERC Order 825

May be impacted by schedules made in day-ahead market

Look-ahead dispatch and intertemporal marginal cost pricing become important pieces

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