UNIVERSITY OF WASHINGTON
ELECTRICAL ENGINEERING

Look-Ahead Strategic Energy Storage in Ramp-Constrained Markets

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Outline

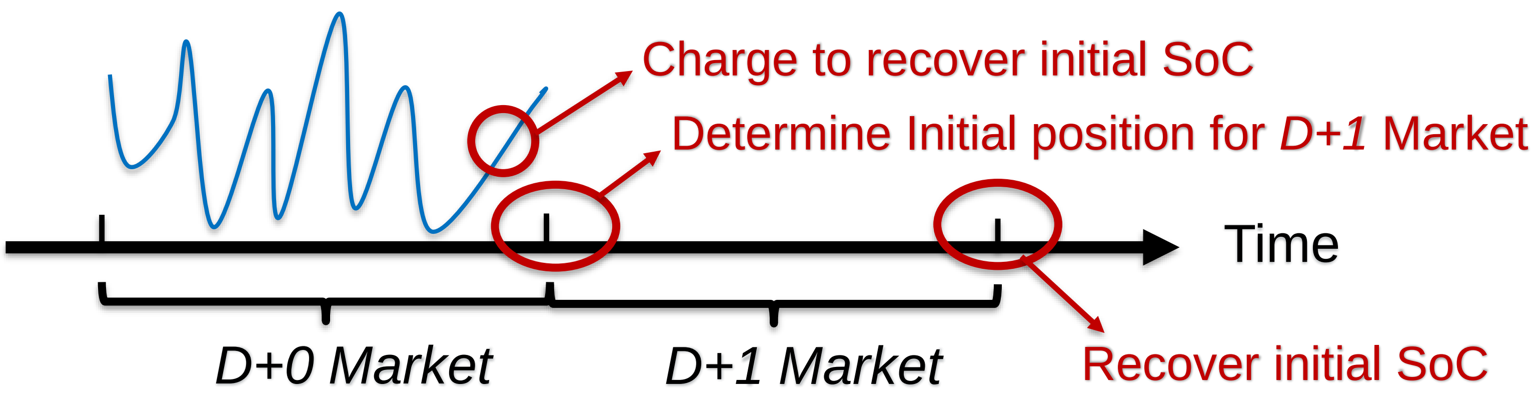
- Introduction
- Formulation
- Numerical Results
- Summary

Introduction

- Previous work on energy storage assumed a vertically integrated context
- Merchant energy storage systems to be deployed soon
- Merchant storage will aim to maximize profit rather than minimize system cost
- Stochastic programming and robust optimization are commonly used with parameterized price uncertainties
- Alternatively, complementarity models can be formulated to analyze the storage/market interactions

Optimized fSoC for *D+1*

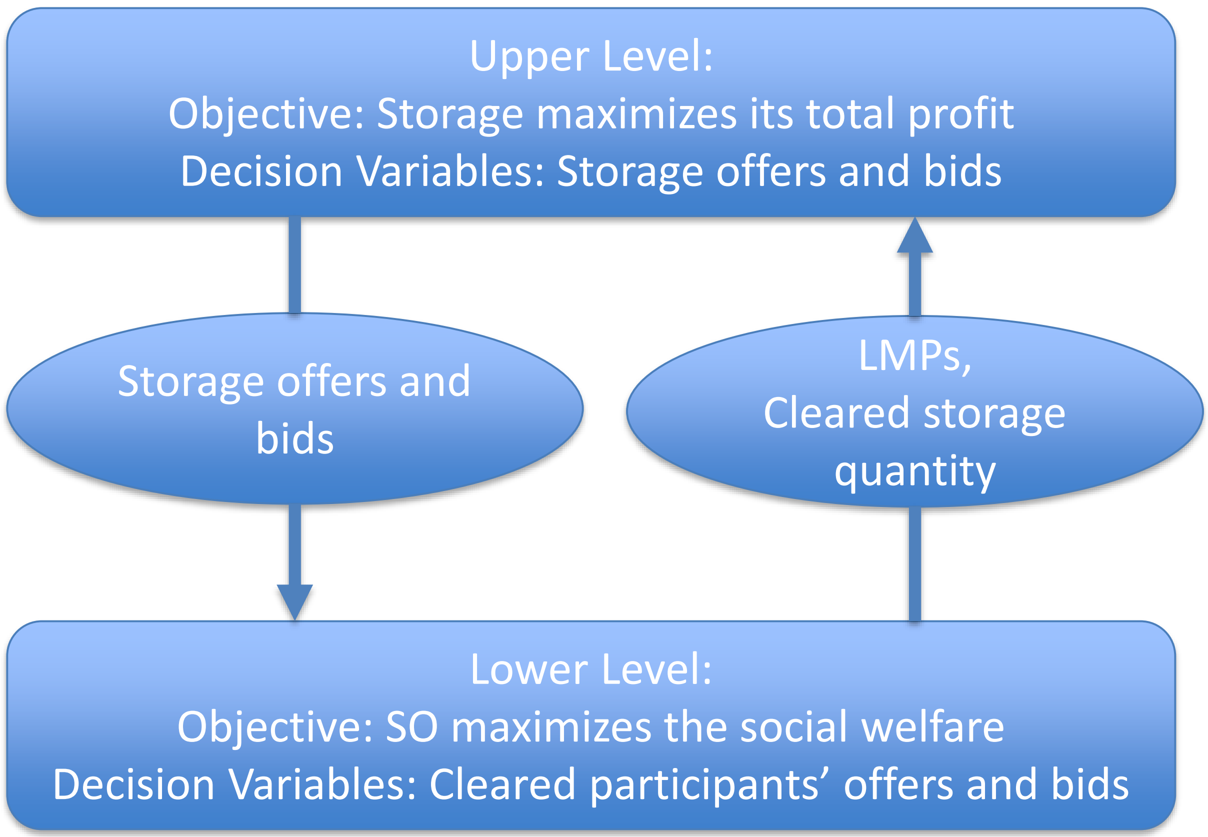
- Storage profitability depends on the SoC levels at the beginning of the planning horizon
- SoC levels at the last operating hour (fSoC) on day D+0 usually fixed at initial SoC levels
- Fixing fSoC on day D+0 limits the potential profits on day *D+1*
- Look-ahead to optimize fSoC



Market Assumptions

- Day-ahead energy market for arbitrage
- Storage optimizes its price-quantity bids
- Both D+0 and D+1 market windows are considered
- Optimized SoC during D+0 (including the last hour)
- Storage discharging/charging is paid/charged at LMPs
- Ramp rates of conventional generators are constrained
- Wind producers offer at $0/MWh
- Demand is elastic and bids in the market

Bilevel Structure



Formulation of the Upper Level Problem

- Energy storage optimizes its price-quantity bids/offers
  - Objective function

$$\max \quad Obj = \Pi^{D_0} + \gamma \Pi^{D_1}$$

D+0 profits

D+1 profits

Formulation of the Upper Level Problem

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D+0 profits — Discount factor for the D+1 profits — D+1 profits

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D+0 profits — Discount factor for the D+1 profits — D+1 profits

  - Upper level decision variables: price-quantity bids, SoC on D+0 and D+1
  - Charging/Discharging limits
  - SoC limits
  - D+1 SoC recovery constraint

Formulation of the Lower Level Problem

- Market is cleared based on the offers of generators and storage and the bids of loads and storage
  - Maximize system social welfare
  - Power balance constraints
  - Thermal generator upper/lower limits
  - Wind upper/lower limits
  - Demand upper/lower limits
  - Storage charging limits
  - Storage discharging limits

Formulation of the Upper Level Problem

- DC power flow model:
  - Voltage angles constraints
  - Transmission capacities constraints
- System thermal flexibility is limited
  - Thermal generator ramp up/down constraints
  - Inter-temporal constraints on conventional generators

Solution Technique

- Lower-level problem is a linear programming problem with given storage offers and bids
- KKT conditions can be derived
- This Mathematical Programming with Equilibrium Constraints (MPEC) problem can be transformed into a single-level equivalent
- The resulting MILP formulation is computational tractable
- A duality-based approach is also applicable (but turns out to be more computationally expensive)

Test System Data

- IEEE RTS 24-bus system with 32 generators, 5 wind farms and 4 storage (locations and sizes are optimized as in [2])
- One representative week is used to test the algorithm
- Wind profiles are from NREL's Eastern Dataset
- Implemented in GAMS and solved with CPLEX

Storage	ES1	ES2	ES3	ES4
Power Rating (MW)	41	17	36	93
Energy Rating (MWh)	303	117	247	629

Effect of the Look-ahead Discount Factor

- Without network constraints and without ramp limits
  - Case 1 : No look-ahead, fSoC = SoC_0 = 50% on day D+0
  - Case 2 : No look-ahead, optimized fSoC on day D+0
  - Case 3 : With look-ahead, discount factor $\gamma = 0.5$
  - Case 4 : With look-ahead, discount factor $\gamma = 1.0$

Case	No Look-ahead, fSoC = SoC_0 = 50%	No Look-ahead, optimized fSoC	With look-ahead, $\gamma = 0.5$	With look-ahead, $\gamma = 1.0$
Profits ($)	45141	62558 (+ 38 %)	66069 (+ 46 %)	59016 (+ 31 %)

Effect of the Look-ahead Discount Factor

- With network constraints and with ramp limits
  - Case 5 : No look-ahead, fSoC = SoC_0 = 50% on day D+0
  - Case 6 : No look-ahead, optimized fSoC on day D+0
  - Case 7 : With look-ahead, discount factor $\gamma = 0.5$
  - Case 8 : With look-ahead, discount factor $\gamma = 1.0$

Case	No Look-ahead, fix fSoC = SoC_0 = 50%	No Look-ahead, optimized fSoC	With look-ahead, $\gamma = 0.5$	With look-ahead, $\gamma = 1.0$
Profits ($)	59672	68218 (+ 14 %)	69400 (+ 16 %)	62326 (+ 5 %)

Effect of the Look-ahead Discount Factor

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  - Case 5 : No look-ahead, fSoC = SoC_0 = 50% on day D+0
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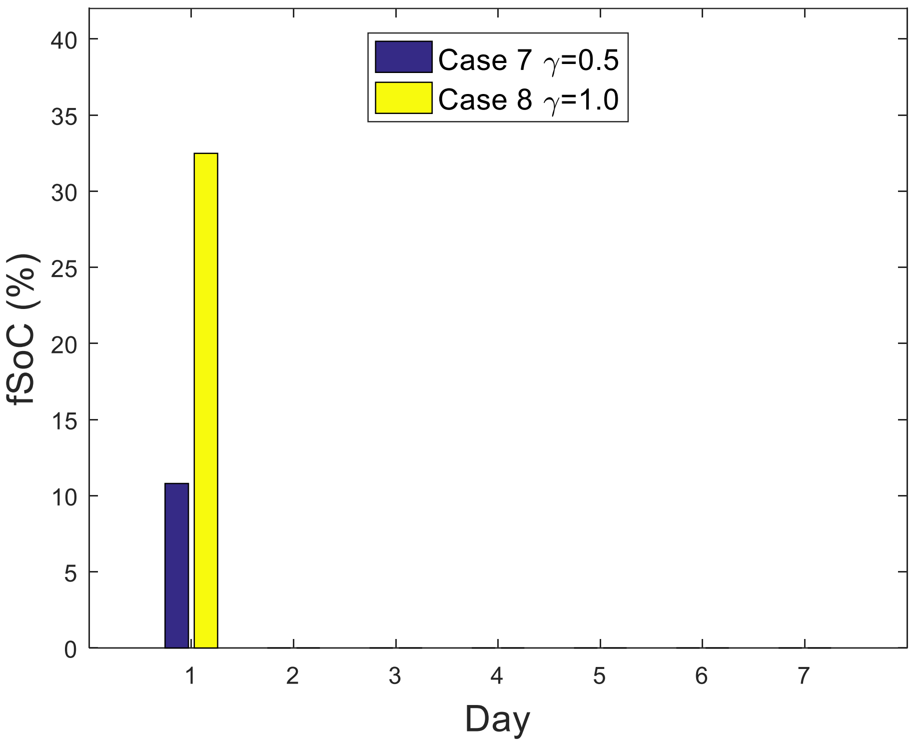
Case	No Look-ahead, fix fSoC = SoC_0 = 50%	No Look-ahead, optimized fSoC	With look-ahead, $\gamma = 0.5$	With look-ahead, $\gamma = 1.0$
Profits ($)	59672	68218 (+ 14 %)	69400 (+ 16 %)	62326 (+ 5 %)
Change from Case 1-4	+ 14531	+ 5660	+ 3331	+ 3310

Effect of the Look-ahead Discount Factor

- Look-ahead bidding changes fSoC



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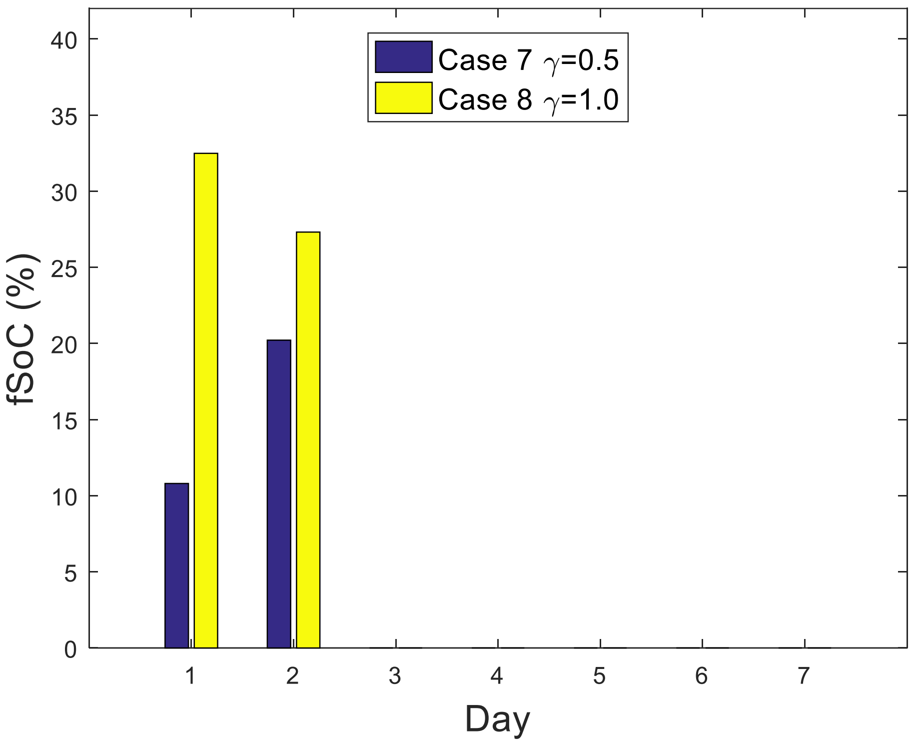

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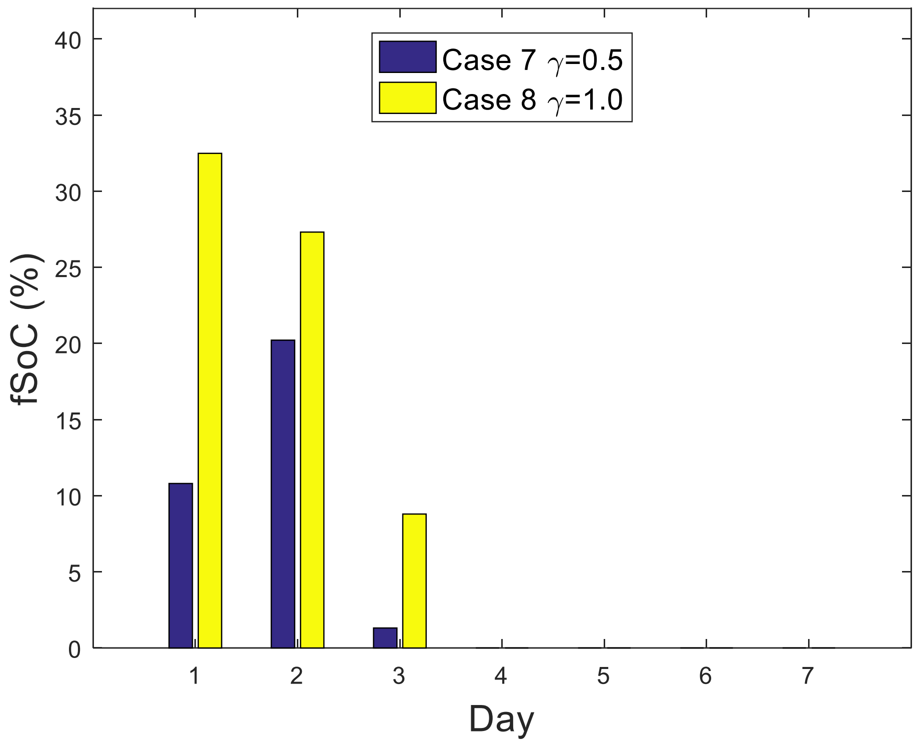

Effect of the Look-ahead Discount Factor

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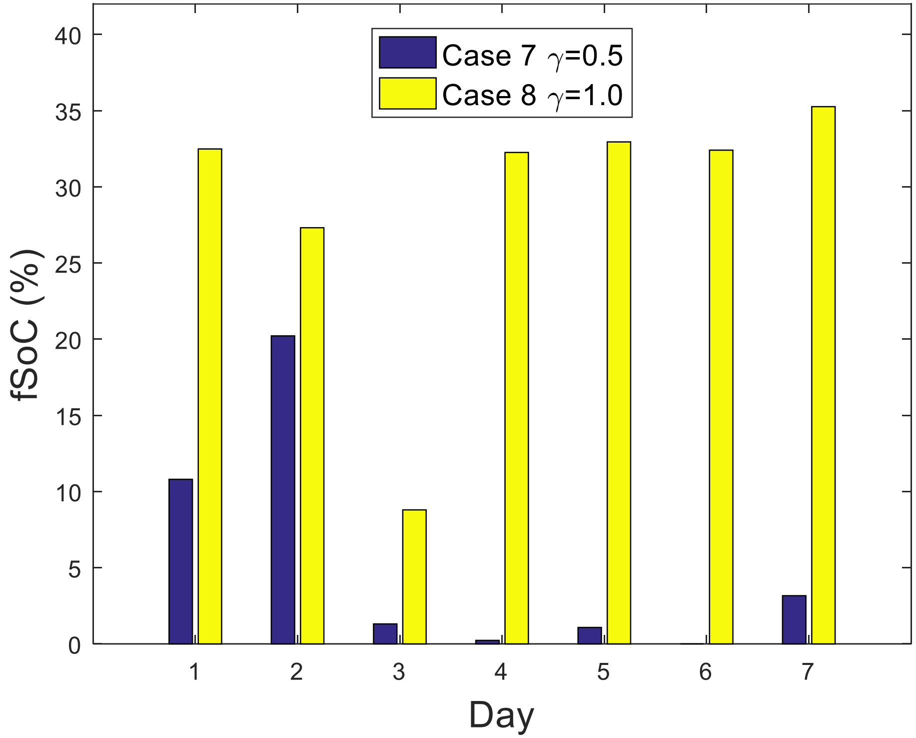
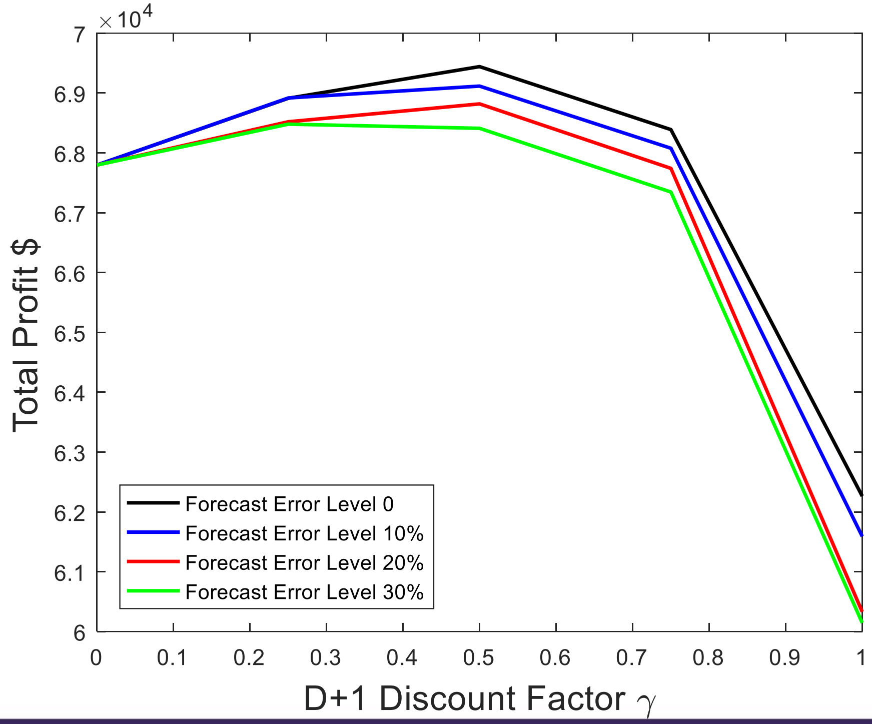


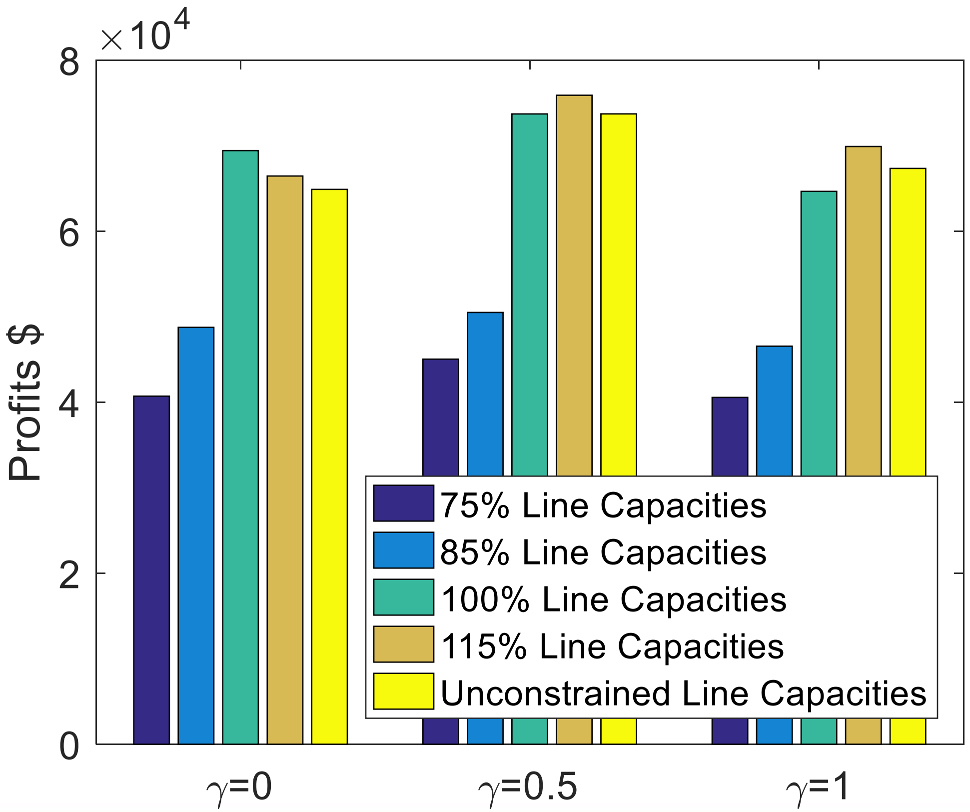
Effect of the *D+1* Forecast Error

- Better forecast results in higher profits
- Discount factor γ should not set too large



Effect of the Transmission Capacity

- Transmission capacity affects storage's ability to perform arbitrage



Summary

- Look-ahead bidding increases storage profits in the day-ahead energy market
- Use proper discount factor to determine good initial SoC level for *D+1*
- Network constraints have a two-fold effect:
  - Generally increase storage's profits
  - Reduce this profit if storage energy cannot be delivered
- Storage takes advantage of the limited ramping capacity in the day-ahead energy market

References

[1] Y. Wang, Y. Dvorkin, R. Fernández-Blanco, and D. S. Kirschen, "Look-ahead Strategic Energy Storage in Ramp-Constrained Market", 2016.

[2] H. Pandzic, Y. Wang, T. Qiu, Y. Dvorkin, and D. S. Kirschen, "Near-optimal method for siting and sizing of distributed storage in a trans-mission network," IEEE Trans. on Power Syst., vol. 30, no. 5, pp. 2288–2300, Sept 2015.

[3] Y. Dvorkin, R. Fernández-Blanco, D. S. Kirschen, H. Pandzic, J.-P. Watson, and C. A. Silva-Monroy, "Ensuring Profitability of Energy Storage," IEEE Trans. On Power Syst., in press.

[4] B. Xu, Y. Dvorkin, D. S. Kirschen, C. A. Silva-Monroy, J.-P. Watson, "A Comparison of Policies on the Participation of Storage in U.S. Frequency Regulation Markets," IEEE PES Gen. Meeting, 2016.

[5] International Energy Agency, "Energy Storage Technology Roadmap," Technical Report, 2014.

[6] NREL, "Renewable Electricity Futures Study," Technical Report, 2012.

THANK YOU!

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