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BRADLEY DEPARTMENT of ELECTRICAL & COMPUTER ENGINEERING

A Game-theoretic Framework to Investigate Conditions for Cooperation between Wind Power Producers and Energy Storage Operators

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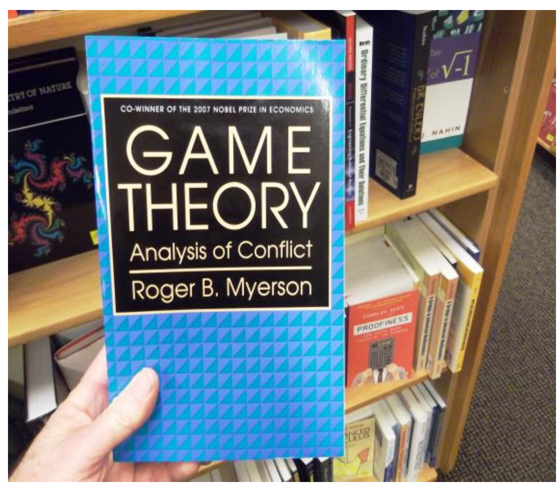
Objective

Wind Power Producer

Cooperate?



Energy Storage Operator

Problem Definition

- Wind is intermittent
- Generation-load mismatch (Imbalance/Deviation)
  - Energy Storage
  - Demand Response
  - Additional Operating Reserves (Ancillary Services)
- Energy storage (Li-ion batteries)
  - Short-term Imbalances - Regulation Service (min-to-min fluctuations)
  - Larger Imbalances - Capacity Firming/Energy Smoothing (hour-to-hour)

Problem Definition…Cont’d

- Current Market
  - Low penetration of renewables (<20%)
  - Utility bears cost of procuring expensive generator reserves
  - No Imbalance Penalties
  - Storage operates independently in energy and reserves markets
- Future Market
  - Increased penetration (20-35%)
  - Utility will offset some cost to wind producers through proposed mechanism of imbalance penalties.
  - Energy Storage Operators may enter into agreements with Wind Power Producers to provide what is promised

Current Approach

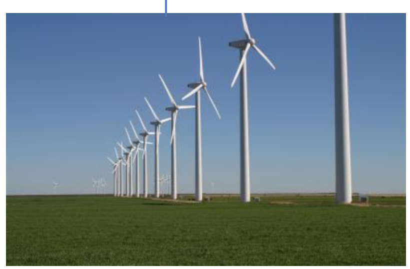
- Optimize sizing, placement and scheduling of energy storage to minimize wind power imbalances (collocated)
- Maximize revenues through independent operation in reserve market (arbitrage/regulation etc.)
- Most problem formulations don’t take into account imbalance penalties imposed on wind power producers
- Studies that take into account imbalance penalties are solely concerned with the optimal contracting of wind power to decrease these penalties and maximize the revenues of the wind power producer

Problem Definition…Cont’d

- Should Energy Storage Operators enter into an agreement with Wind Power Producers to balance any wind deviations?

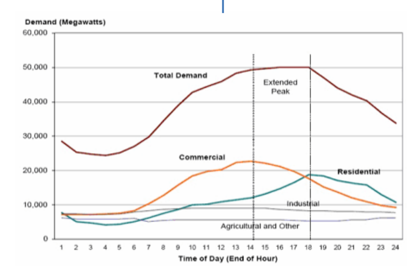
Network Model

Utility



Wind Power Producer

Energy Storage Operator



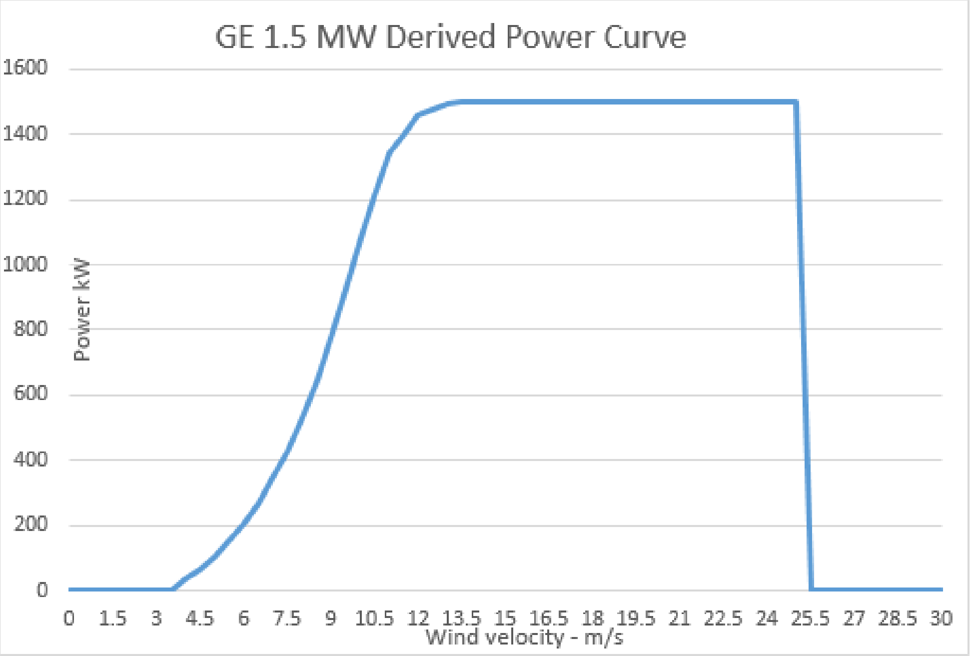
Load Entity

Model Assumptions and Parameters

Variable Name	Variable Definition	Variable Value
S	Storage Size	4 MWh
$SOCC_t, S_t$	State of Charge at time 't'	
γ_c , eff	Charging/Discharging Efficiency of Storage Device	0.9
γ_s	Self-Discharge Rate of Storage Device	1
T	Time Period	1 hour
$\bar{q}^D$, $Dlim$	Discharge Limit	1MW
$\bar{q}^R$, $Clim$	Charge Limit	1MW
q_t^R	Quantity purchased through arbitrage at time 't'	
q_t^D	Quantity sold through arbitrage at time 't'	
q_t^{RU}	Quantity of UP regulation offered into the market at time 't'	
q_t^{RD}	Quantity of DOWN regulation offered into the market at time 't'	
P_t	Day-Ahead Electricity Market Price (LMP) at time 't' - $/MWh	
P_t^{RU}	Market Clearing Price for UP regulation at time 't' - $/MWh	
P_t^{RD}	Market Clearing Price for DOWN regulation at time 't' - $/MWh	
C_d	Cost of Discharging at time 't' ($/MWh)	0
C_r	Cost of Charging at time 't' ($/MWh)	0

Game-theoretic Framework

- Wind Model
  - Extrapolation of Data from 50m to 80m
  - Wind Power Output
  - Persistence Model



- Load Model

Game-theoretic Framework…Cont'd

- Wind Deviation/Variability

$\Delta\bar{w}_t < 0$ – STORAGE DISCHARGING REQ.

$\Delta\bar{w}_t > 0$ – STORAGE CHARGING REQ.

- Load Deviation/Variability

$\Delta\bar{l}_t < 0$ – STORAGE CHARGING REQ.

$\Delta\bar{l}_t > 0$ – STORAGE DISCHARGING REQ.

- Net Deviation/Variability

$$\Delta\bar{n}_t = \Delta\bar{w}_t - \Delta\bar{l}_t$$

Game-theoretic Framework…Cont'd

- Energy Storage Model
  - Balancing Deviations

$$N_t = \max(\min(x_1, \min(S - x2, \bar{q}^R)), \max(-x_2, -\bar{q}^D))$$

$$x_1 = change\ in\ stored\ energy,\ x_2 = stored\ energy$$

  - Maximizing Revenues (Arbitrage + Reg. Service)

$$\min_x f^T x \text{ such that } \begin{cases} Ax \le b \\ A_{(eq)}x = b_{eq} \\ lb \le x \le ub \end{cases}$$

$$x = [q_1^D \quad \cdots \quad q_T^D \quad q_1^R \quad \cdots \quad q_T^R \quad q_1^{RU} \quad \cdots \quad q_T^{RU} \quad q_1^{RD} \quad \cdots \quad q_T^{RD}]'$$

Pay-off Matrix

STORAGE \ WIND	COOPERATION	NON-COOPERATION
COOPERATION	B (Case 1) A	D (Case 2) C
NON-COOPERATION	F (Case 4) G	D (Case 3) E

Case 1

- Energy storage has four streams of revenue:
  - Balancing Wind deviations ($\Delta\overline{w}_t$).
  - Balancing Load deviations ($\Delta\overline{l}_t$)
  - Arbitrage
  - Regulation Service

- Wind Power Producer pays an imbalance fee (∂_1^i,∂_1^e) to the storage and may also pay penalty (∂_2^i,∂_2^e) to the utility

Case 2

- Energy Storage has four streams of revenue:
  - Balancing Load Deviations ($\Delta \bar{l}_t$)
  - Balancing Wind Deviations ($\Delta \bar{w}_t$)
  - Revenue from Arbitrage
  - Revenue from Regulation Service

- Wind Power Producer pays penalty ($\partial_2^i, \partial_2^e$) to the utility

Case 3

- Energy Storage has three streams of revenue:
  - Balancing Net Deviations ($\Delta\bar{n}_t$)
  - Arbitrage
  - Regulation Service

- Wind Power Producer chooses to not cooperate and pays the penalty (∂_2^i,∂_2^e) to the utility

Case 4

- Energy Storage has three streams of revenue:
  - Balancing Net Deviations ($\Delta\bar{n}_t$)
  - Arbitrage
  - Regulation Service

- Wind Power Producer pays the penalties (∂_2^i,∂_2^e) to the utility. Penalty is paid only on underproduction. Overproduction is curtailed

Results – January (Base Case)

WIND / STORAGE	COOPERATION	NON-COOPERATION
COOPERATION	$707 $6,988	$195 $8,514
NON-COOPERATION	$2,108 $5,422	$195 $4,870

WIND / STORAGE	COOPERATION	NON-COOPERATION
COOPERATION	A=$707 A=$4,645 B=$2,343	A=$195 A=$8,514 B=$0
NON-COOPERATION	A=$2,108 A=$5,422 B=$0	A=$195 A=$4,870 B=$0

Discussion

- Wind power producer's cooperative strategy dominates its non-cooperative strategy
- Energy storage operator's cooperative strategy dominates its non-cooperative strategy
- There is a unique pure-strategy Nash Equilibrium in all the cases studied and cooperation is self-enforcing.

Conclusion

- Game-theoretic Framework can be used as an effective tool to study behavior of two independent players, namely wind power producer and energy storage
- Imbalance Penalties are a necessary condition for cooperation
- Game equilibrium does not depend on storage parameters even when stretched to their limits
- Game equilibrium is unchanged across seasons – winter, spring, summer and fall

Future Work

- Model the other streams of revenue for the storage (spinning /non-spinning reserves, voltage support etc.)
- Allow wind power producers to participate in the ancillary services market
- Model a three player game with the utility as a player

Thank You!