Value of Flexible Resources in Wind-Integrated Markets: A Stochastic Equilibrium Analysis

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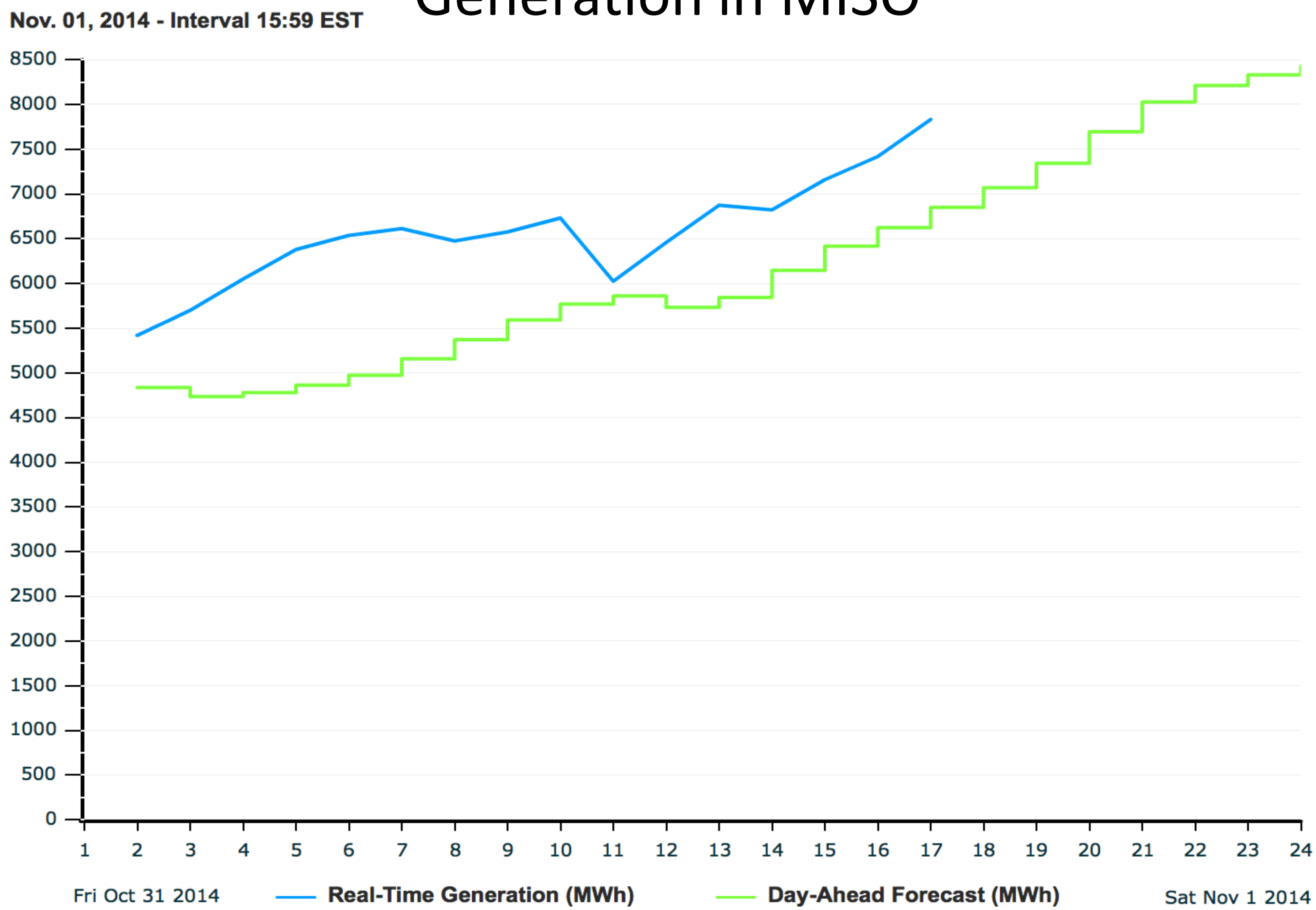
Stochastic Production: Wind Power

Day Ahead Wind Forecast vs. Real Time Wind Generation in MISO



Motivation

- Large penetration of stochastic generation leads to
  - Huge deviations in net load from day-ahead to real-time
  - Increased needs for reserves
- Uncertainty makes scheduling challenging (wrong unit commitment decisions)
- Flexible resources can cope with load deviations in real time
  - Peak units (CCGT)
  - Demand response (slow/fast), Storage
  - Virtual bidding
- New solution approach is needed
  - <u>Stochastic modeling instead of deterministic</u>

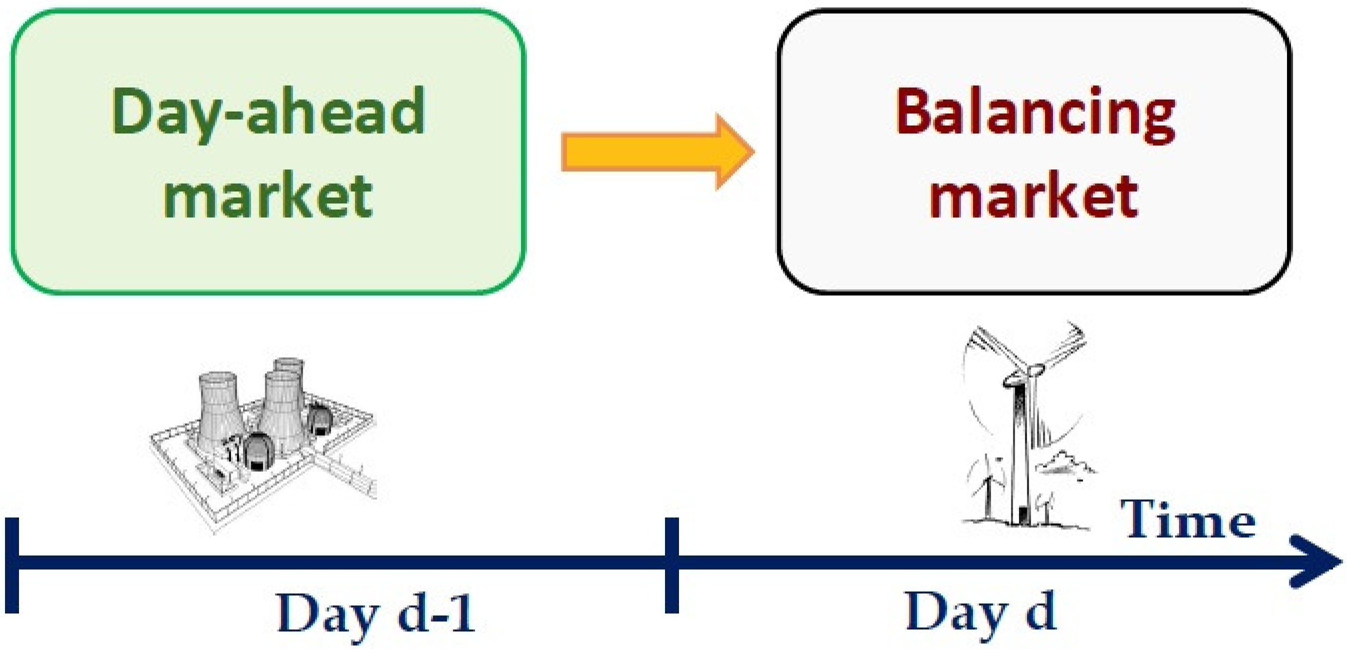
Research Questions

- What is the cost of uncertainty in generation?
- What is the value of flexible resources?
- What is the value of virtual bidding?

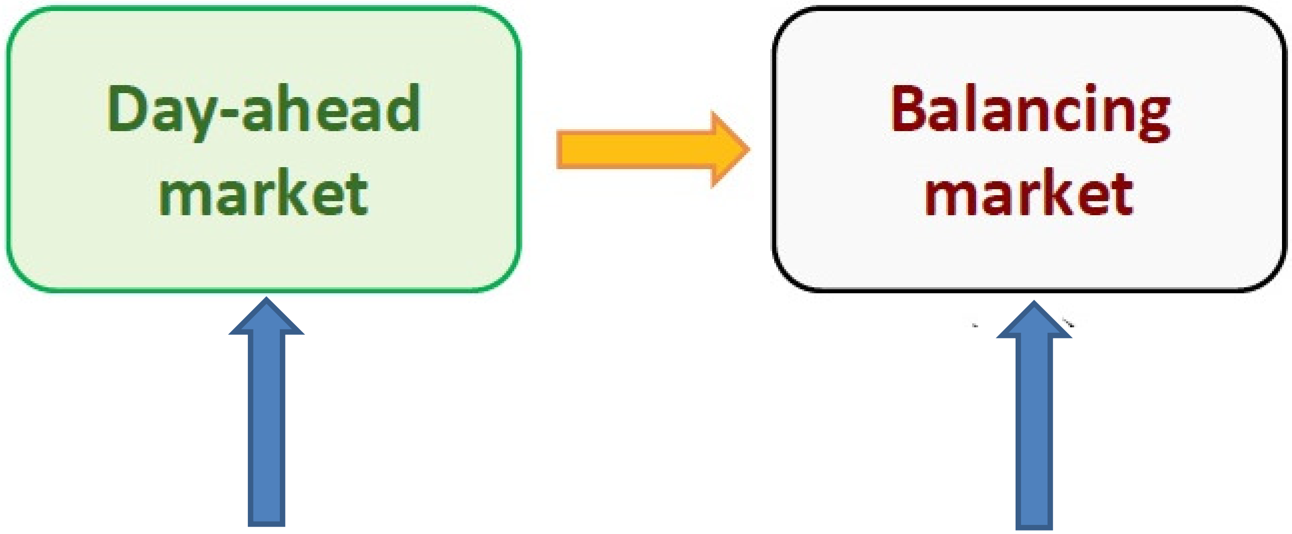
Problem Statement
(Two-stage Settlement – 1 Day Horizon)

Uncertainty ↑ (stochastic production ↑)

Flexibility ↓ ⇒ Balancing costs ↑



Problem Statement
(Two-stage Settlement – 1 Day Horizon)



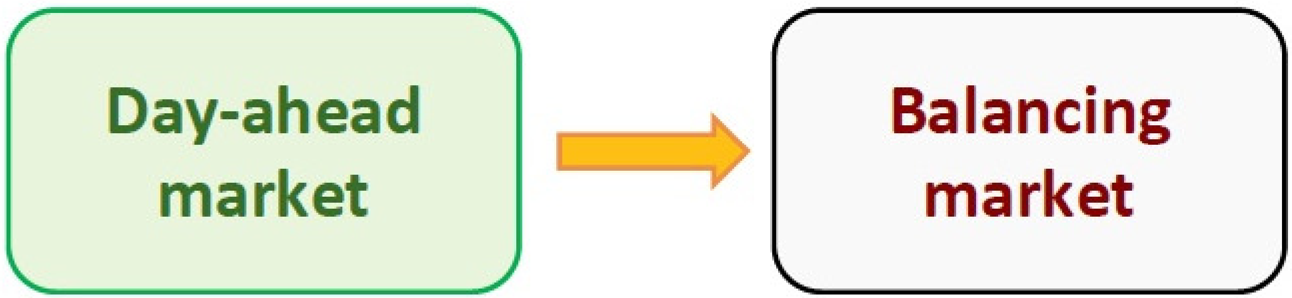
Wind Scenario Set: S^{DA} ={s_1,…, s_n}
(Based on available forecasted data in day-ahead)

Wind Scenario Set: S^{RT} ={w_1,…, w_m}
(Based on available forecasted data in real-time)

- For the sake of simplicity, a single DA scenario (deterministic) is assumed here!

Problem Statement
(Two-stage Settlement – 1 Day Horizon)

SID: Scenario-<u>independent</u> decisions
SDD: Scenario-<u>dependent</u> decisions

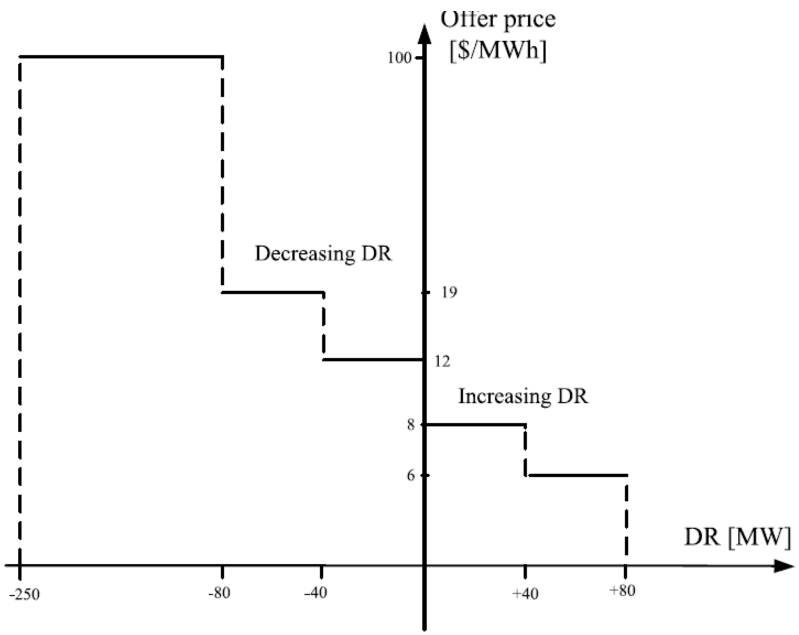


- Slow gen commitment: SID (u)
- Fast gen commitment SDD (u)
- Gen energy: SDD (p^{DA})
- Slow DRs: SID (d^{DA})
- Fast DRs: SDD (d^{DA})
- Virtual arbitrager: SID (v^{DA})

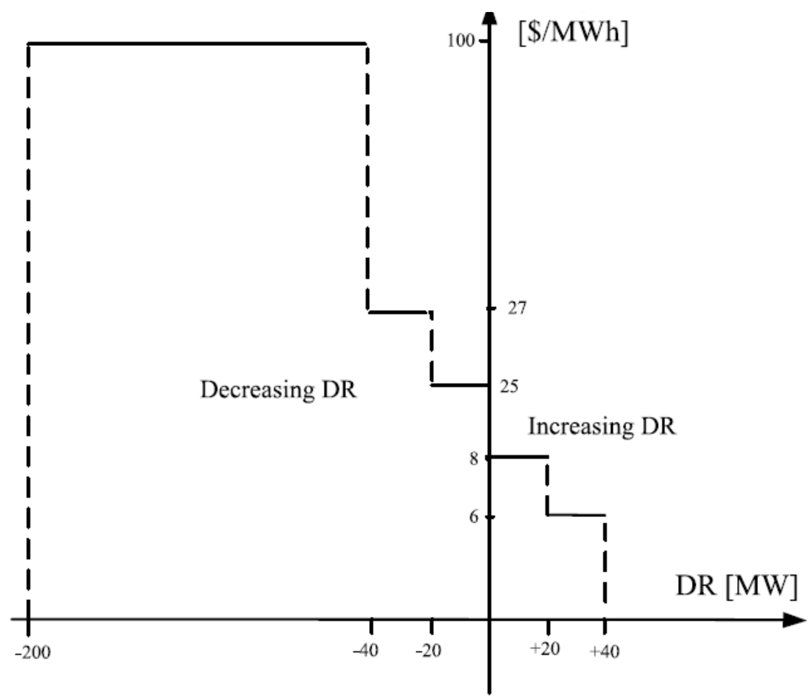
- Slow generators: (u: fixed,p^{RT}: SDD)
- Fast generators: (u: SDD ,p^{RT}: SDD)
- Slow DRs: fixed
- Fast DRs: SDD (d^{RT})
- Virtual arbitrager: SID (v^{RT})

Problem Statement
(Slow DR vs. Fast DR)

Slow DR (available in the day-ahead market)



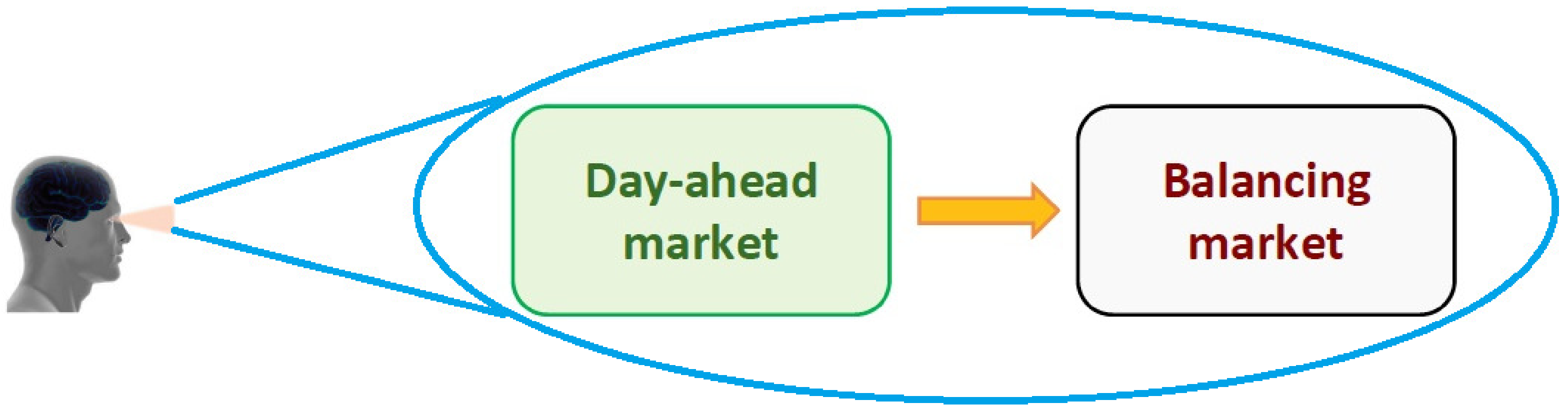
Fast DR (available in the RT market)



DR MW available: More in day-ahead market

Cost of DR: Higher in RT market

Problem Statement (Equilibrium Analysis)



Equilibrium Analysis:

- To gain insight into DA and RT market functioning
- To characterize interactions between two markets
- To evaluate the cost of uncertainty
- To evaluate the value of flexibility

Contributions

Three Equilibrium Models:

1) Multi-player equilibrium model:
   - Each player maximizes its expected profit in DA & RT markets, considering them simultaneously. Each player is price taking.

2) Total cost minimization:
   - A single optimization problem whose objective function is to minimize the total expected cost of both DA and RT markets.

3) Two-stage settlement equilibrium model:
   - First DA market clears, then RT market
   - Each stage's market clearing problem is a cost minimization assuming all gen and DR bids truthfully; no self-scheduling
   - Virtual arbitragers consider both markets simultaneously and maximize profit.

Model 1: Multi-player Equilibrium Model

Each generator:

Max E(profit)
By choosing DA and RT unit commitment and production levels
S.t.: Generation constraints
Relaxed unit commitment

Virtual arbitrager:

Max E(profit)
By choosing DA and RT arbitrage quantities
S.t.: $V^{DA}+V^{RT}=0$

Grid Operator

Max E(profit)
By choosing network flows
S.t.: Balancing constraints
- Network limits (in DA and RT)

Demand Response:

Max E(profit)
By choosing DA and RT DR quantities
S.t: DR quantity limits (DA and RT)

Market clearing:

- Energy balances DA (Price DA)
- Energy balances RT (Price RT)

Model 1: Multi-player Equilibrium Model

To be solved together!

Each generator:

KKT Conditions

Virtual arbitrager:

KKT Conditions

Grid Operator

KKT Conditions

Demand Response:

KKT Conditions

Market clearing:

- Energy balances DA (Price DA)
- Energy balances RT (Price RT)

Model 2: Total Cost Minimization

A single optimization problem:

Min [E(cost) DA] + [E(cost) RT]

Subject to:

- Production, ramping and start-up limits of generators (in DA and RT)
- Network limits (in DA and RT)
- DR limits (in DA and RT)
- $V^{DA}+V^{RT}=0$
- Energy balances DA
- Energy balances RT

Model 3: Two-stage Settlement Equilibrium Model

DA market clearing:

Min [E(cost) DA]
S.t.:
- Production, ramping& start-up limits of generators (in DA)
- Network limits (in DA)
- DR limits (in DA)
- Energy balances (in DA)

Each virtual arbitrager:

Maximize expected profit subject to:
$V^{DA}+V^{RT}=0$

RT market clearing for each RT scenario:

Minimize [Cost in RT]
subject to:
- Production, ramping & start-up limits of generators (in RT)
- Network limits (in RT)
- DR limits (in RT)
- Energy balances (in RT)

Model 3: Two-stage Settlement Equilibrium Model

To be solved together!

DA market clearing:

KKT Conditions

Each virtual arbitrager:

KKT Conditions

RT market clearing for each RT scenario:

KKT Conditions

Modeling and Solution Approach

Unit commitment constraints are formulated as TRUC (Tight Relaxed Unit Commitment) problem (S. Kasina, S. Wogrin, B.F. Hobbs, JHU Working Paper, Nov. 2014.)

Multi-player equilibrium model is solved by solving the KKT conditions of all players simultaneously.

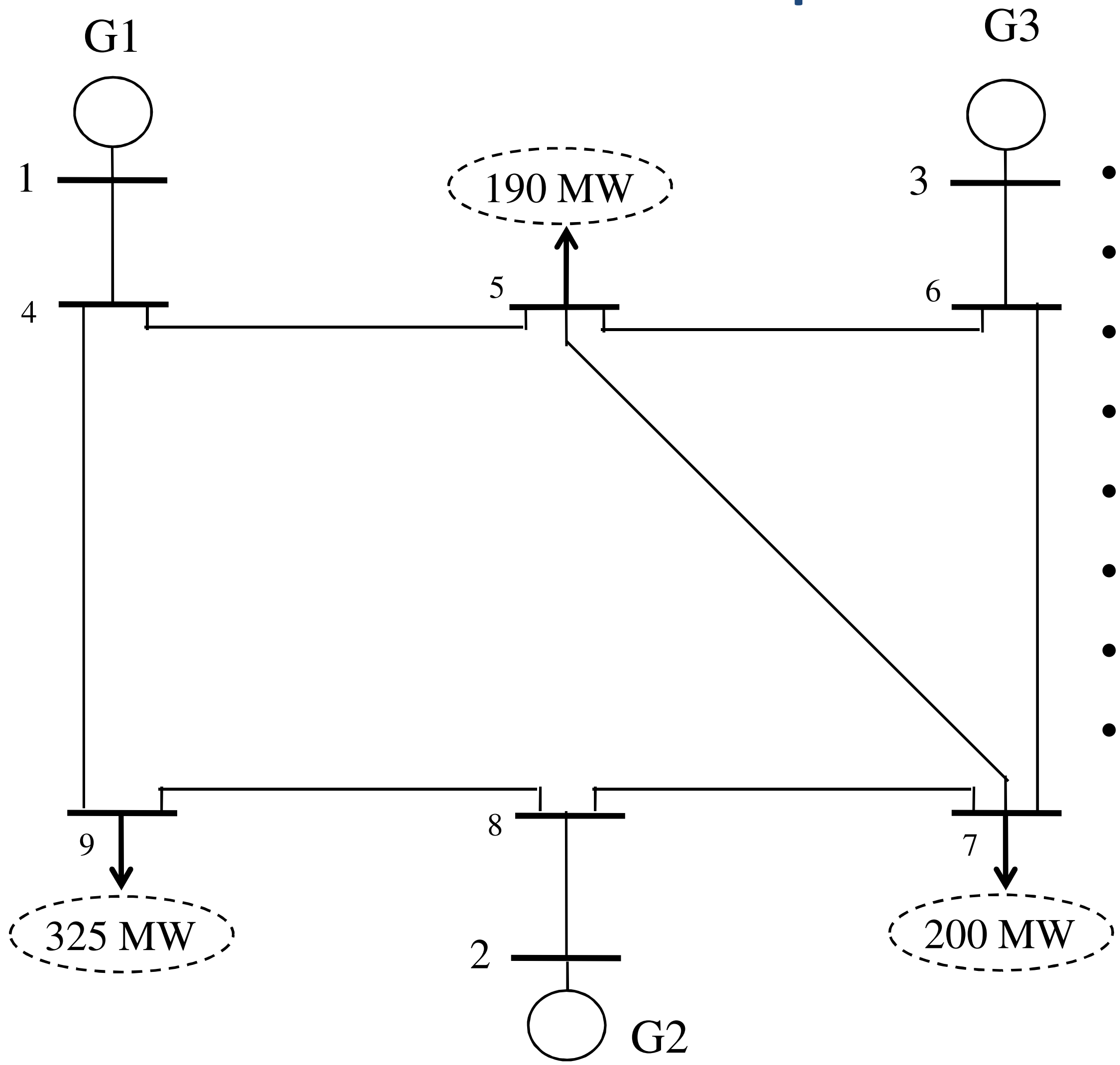
Two-stage settlement market clearing problems solved by solving the KKTs of DA market, RT market and arbitrager simultaneously (more realistic)

Analytical Results

Multi-player equilibrium model (Model 1) is equivalent to total cost minimization (Model 2) (proved: identical set of KKT conditions)

Without VB, Two-stage settlement market clearing is NOT equal to Models 1 and 2 (proved)

Example Network



- 9-bus test system
- Time period: 3 hours
- T1 is off peak and no DR
- T2 is peak and DR
- T3 is shoulder and DR
- Demand in DA is 779 MW
- Demand in RT is 794 MW
- A single wind farm in node 3

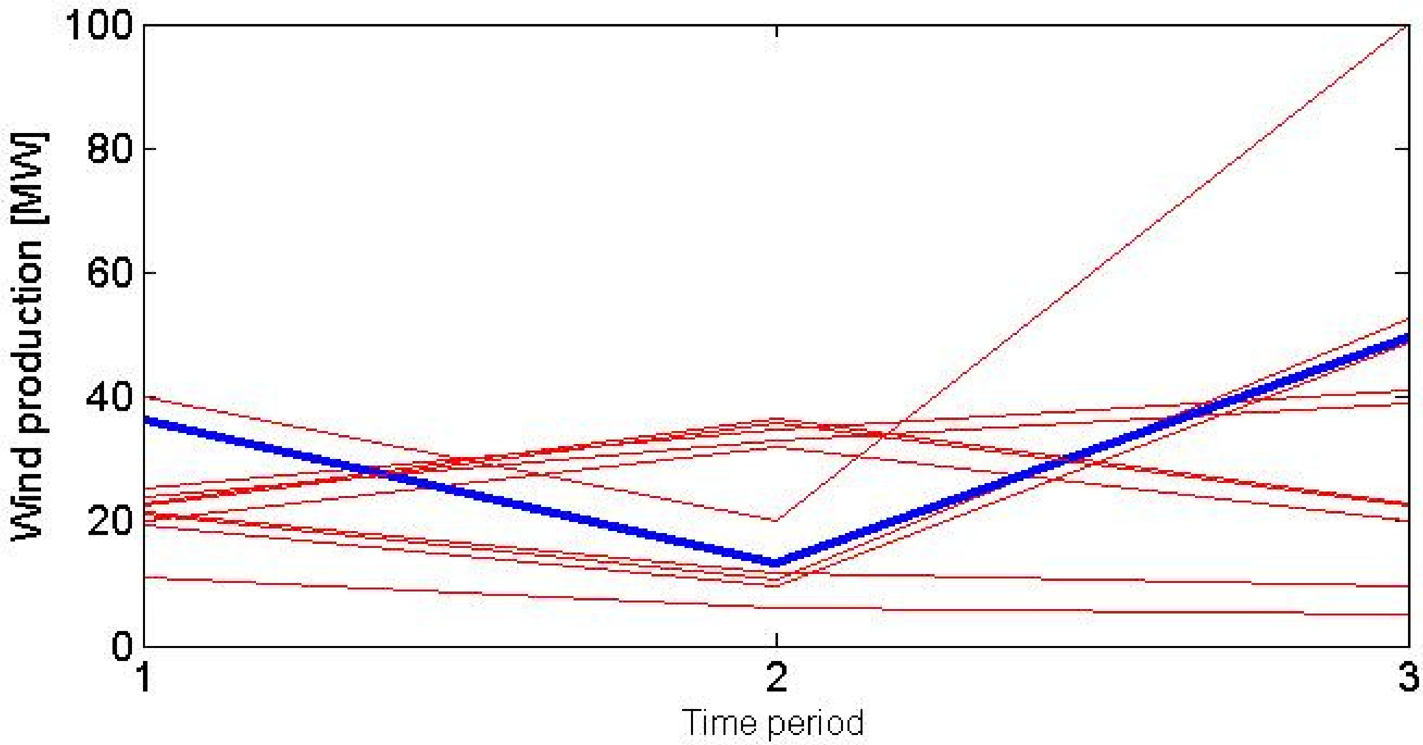
Example: Data

Each responsive load in the day-ahead market (slow DR) is able to increase/decrease at most 6% of its consumption during peak and shoulder hours.

Each responsive load in the real-time market (fast DR) is able to increase/decrease at most 2% of its consumption during peak and shoulder hours.

Example: Wind Forecast

Single DA scenario and 10 RT scenarios



Installed wind capacity is 12 % of average load

Example: Generator Characteristics

Generator	Type	Min Production (MW)	Capacity (MW)	Ramp up (MW)	Ramp Down (MW)	Start Up cost ($)	Initial Commitment	Initial Prod (MW)	Marginal Cost ($/MWh)
1	Slow	300	300	300	300	90000	1	300	15.6
2	Slow	251	444	107	192	28714	1	251	26.3
3	Slow	70	150	70	80	19004	0	0	33.1
4	Fast	10	100	90	90	8700	0	0	55.3

Offer Price of Downward Slow DR is: 60 ($/MWh) for 3% and 70 ($/MWh) for next 3% and 1000 ($/MWh) for remaining

Offer Price of Downward Fast DR is: 80 ($/MWh) for 1% and 100 ($/MWh) for next 1% and 1000 ($/MWh) for remaining

Bid Price of Upward Slow/Fast DR is: 20 ($/MWh) for 3/1% and 15($/MWh) for next 3/1%

Example

TEC: Total Expected Cost ($)
TELS: Total Expected Load Shed (MWh)

Model/Case	**• No DR • 3 slow units • No fast unit**	**• No DR • 3 slow and 1 fast units**	**• With DR • 3 slow and 1 fast units**
Multi-player equilibrium (Models 1,2)	TEC = 71846 TELS = 0.3	TEC = 66711 TELS = 0	TEC = 63485 TELS = 0
Two-stage market clearing (Model 3) (No VB)	TEC = 97285 TELS = 10.9	TEC = 75050 TELS = 3.3	TEC = 63809 TELS = 0
Two-stage market clearing (Model 3) (with VB)	TEC = 71846 TELS = 0.3	TEC = 66711 TELS = 0	TEC = 63485 TELS = 0

Virtual Bidding (VB)

Can the virtual arbitrager always fix the inconsistencies?

Virtual Bidding (VB)

Can the virtual arbitrager always fix the inconsistencies?

Answer: No!

Virtual Bidding (VB): Counter Example

Generator	Type	Min Production (MW)	Capacity (MW)	Ramp up (MW)	Ramp Down (MW)	Start Up cost ($)	Initial Commitment	Initial Prod (MW)	Marginal Cost ($/MWh)
1	Slow	1000	1000	1000	1000	0	1	1000	50
2	Slow	0	1000	500	500	10000	0	0	60
3	Fast	0	500	500	500	0	0	0	100

Only one hour

Demand in the DA market: 1000 MW
Demand in the RT market: 1000 MW

Wind production based on the DA forecast (single scenario): 250 MW

Wind production based on the RT forecast (scenario 1): 0 MW
Wind production based on the RT forecast (scenario 2): 500 MW

Counter Example

Model/Case	Total expected cost ($)
Multi-player equilibrium (Models 1,2)	45000
Two-stage market clearing (Model 3) (No VB)	50000
Two-stage market clearing (Model 3) (with VB)	50000

Conclusions

- Formulated three different equilibrium models
- DR resources, flexible generators and virtual bidding lower expected total cost of generation

Future Research

- To include storage and load shifting as additional sources of flexibility
- Model 3 to be extended to allow self-scheduling by flexible generators
- To consider imperfect markets instead of competitive ones

Thanks for your attention!