

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

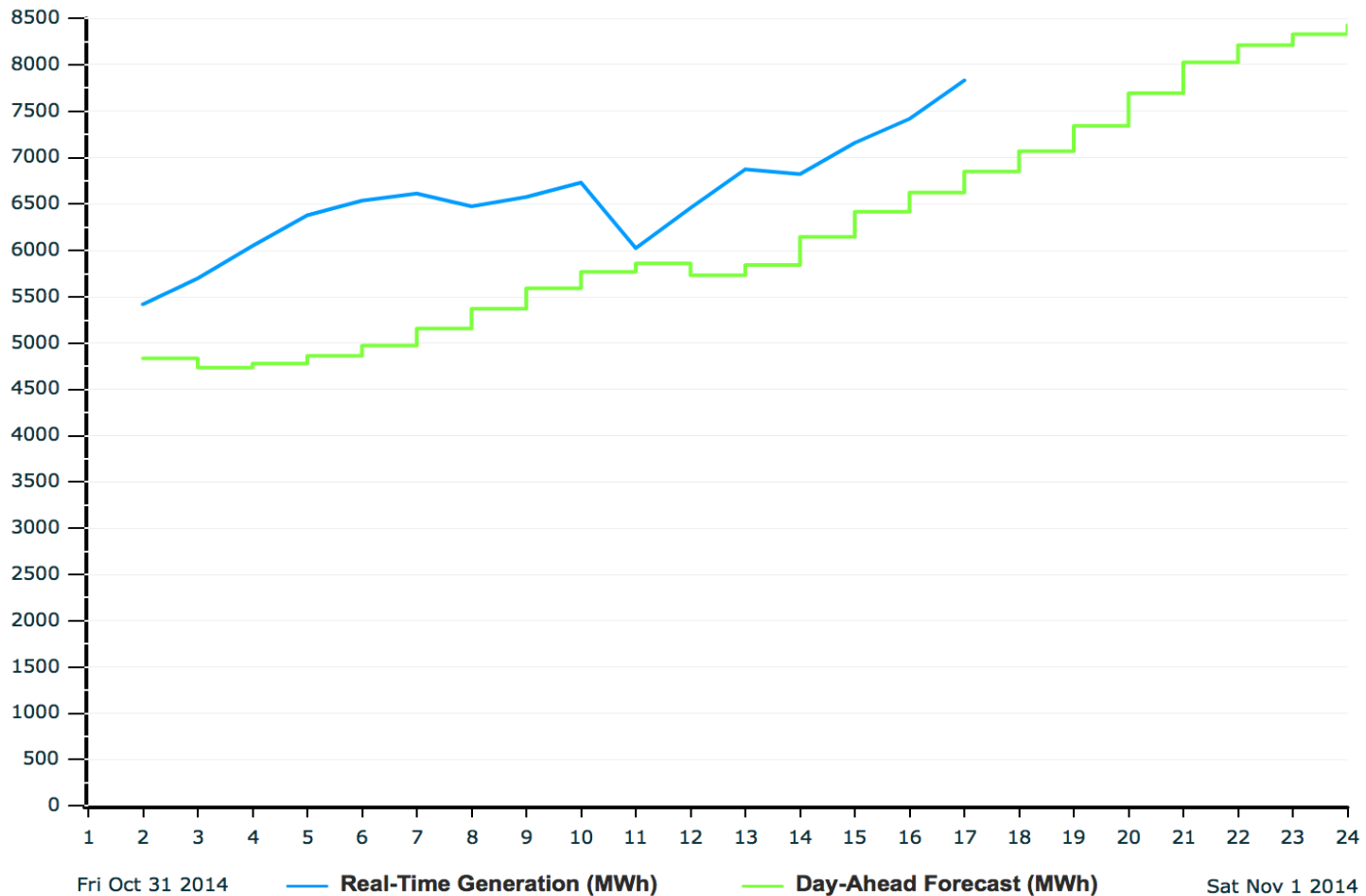


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# Stochastic Production: Wind Power

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

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# 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
  - Stochastic modeling instead of deterministic

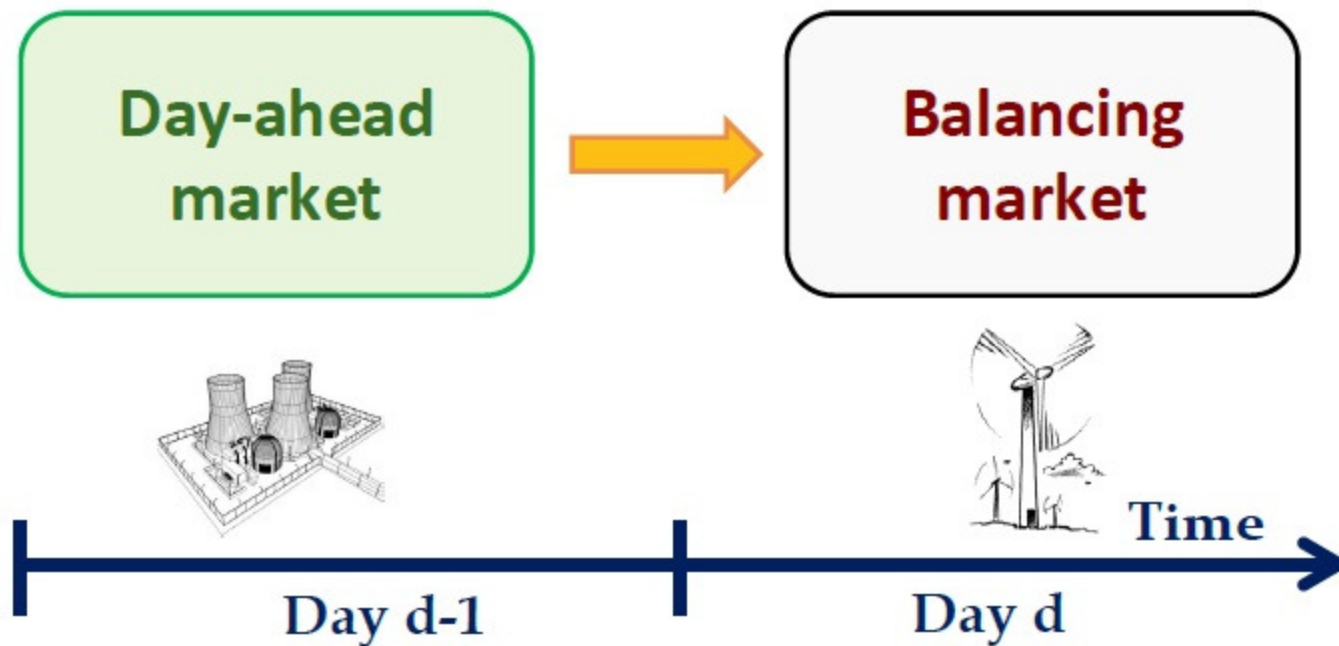
# Research Questions

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

# Problem Statement

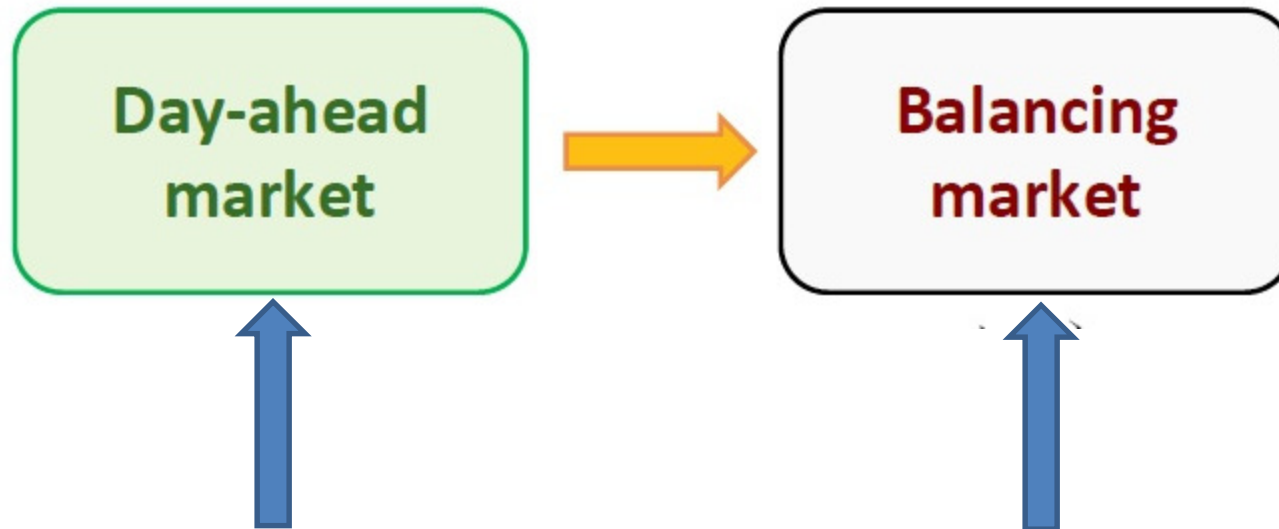
## (Two-stage Settlement – 1 Day Horizon)

Uncertainty  $\uparrow$  (stochastic production  $\uparrow$ )  
Flexibility  $\downarrow \Rightarrow$  Balancing costs  $\uparrow$



# Problem Statement

## (Two-stage Settlement – 1 Day Horizon)



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

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

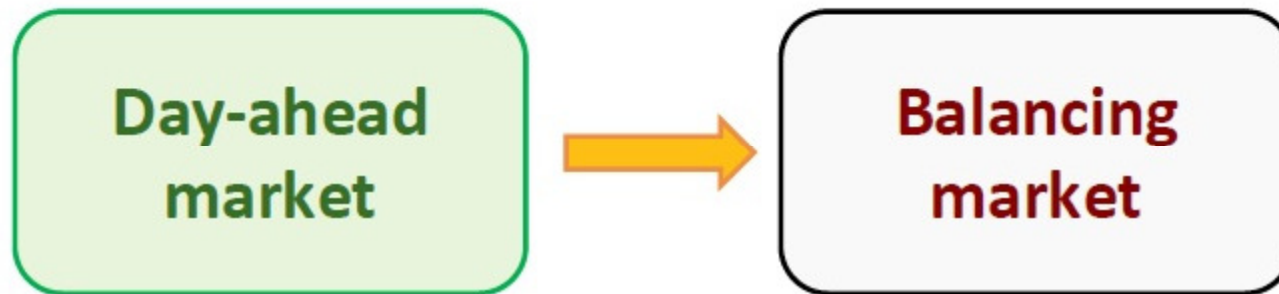
- For the sake of simplicity, a single DA scenario (deterministic) is assumed here!

# Problem Statement

## (Two-stage Settlement – 1 Day Horizon)

**SID:** Scenario-independent decisions

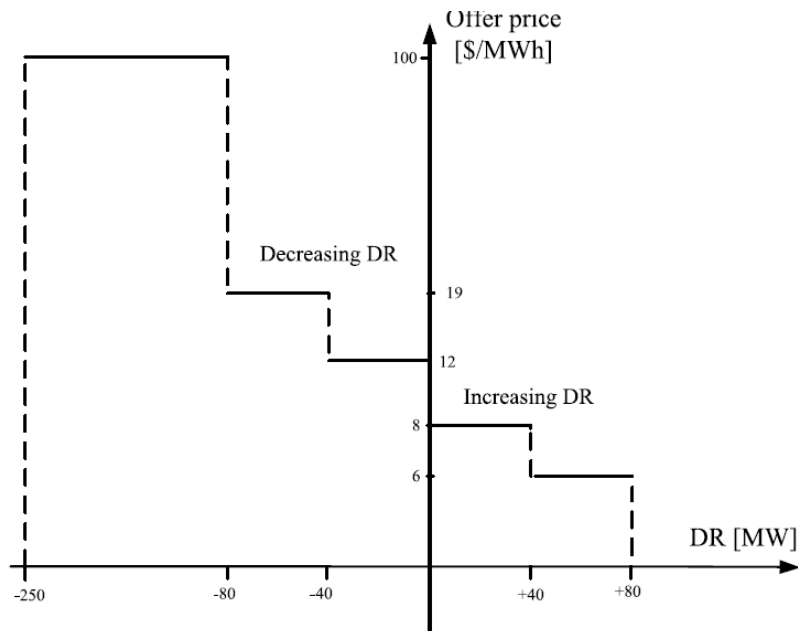
**SDD:** Scenario-dependent decisions



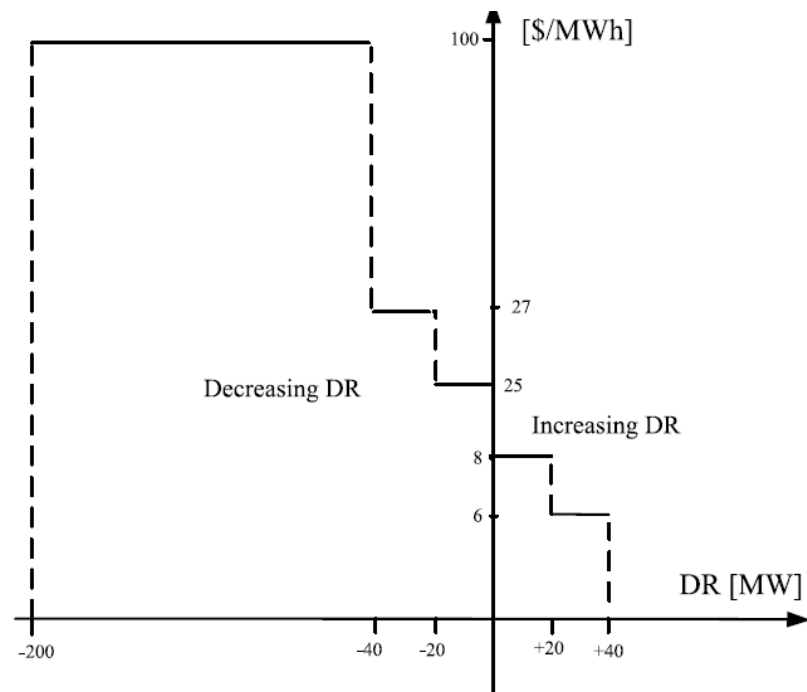
- Slow gen commitment: **SID** ( $u$ )
  - Fast gen commitment **SDD** ( $u$ )
  - Gen energy: **SDD** ( $p^{DA}$ )
  - Slow DRs: **SID** ( $d^{DA}$ )
  - Fast DRs: **SDD** ( $d^{DA}$ )
  - Virtual arbitrage: **SID** ( $v^{DA}$ )
- Slow generators: ( $u$ : **fixed**,  $p^{RT}$ : **SDD**)
  - Fast generators: ( $u$ : **SDD**,  $p^{RT}$ : **SDD**)
  - Slow DRs: **fixed**
  - Fast DRs: **SDD** ( $d^{RT}$ )
  - Virtual arbitrage: **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)

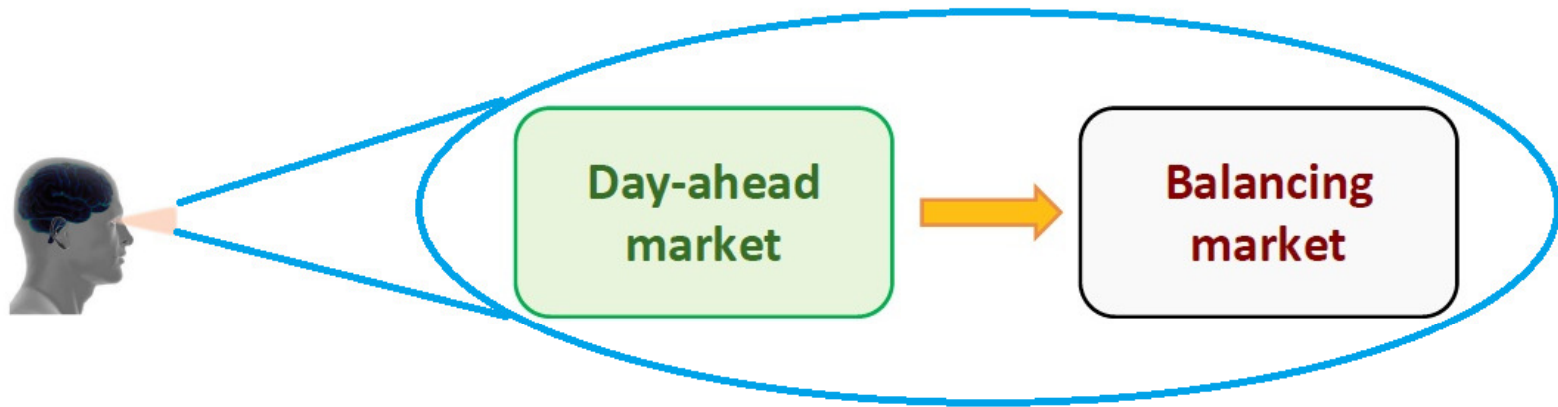


DR MW available: More in day-ahead market

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  $E(\text{profit})$   
By choosing DA and RT unit  
commitment and production levels  
S.t.: Generation constraints  
Relaxed unit commitment

## Virtual arbitrageur:

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

## Grid Operator

Max  $E(\text{profit})$   
By choosing network flows  
S.t.: Balancing constraints  
• Network limits (in DA and RT)

## Demand Response:

Max  $E(\text{profit})$   
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 arbitrageur:

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 arbitrageur:

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 arbitrageur:

**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 arbitrageur simultaneously (more realistic)

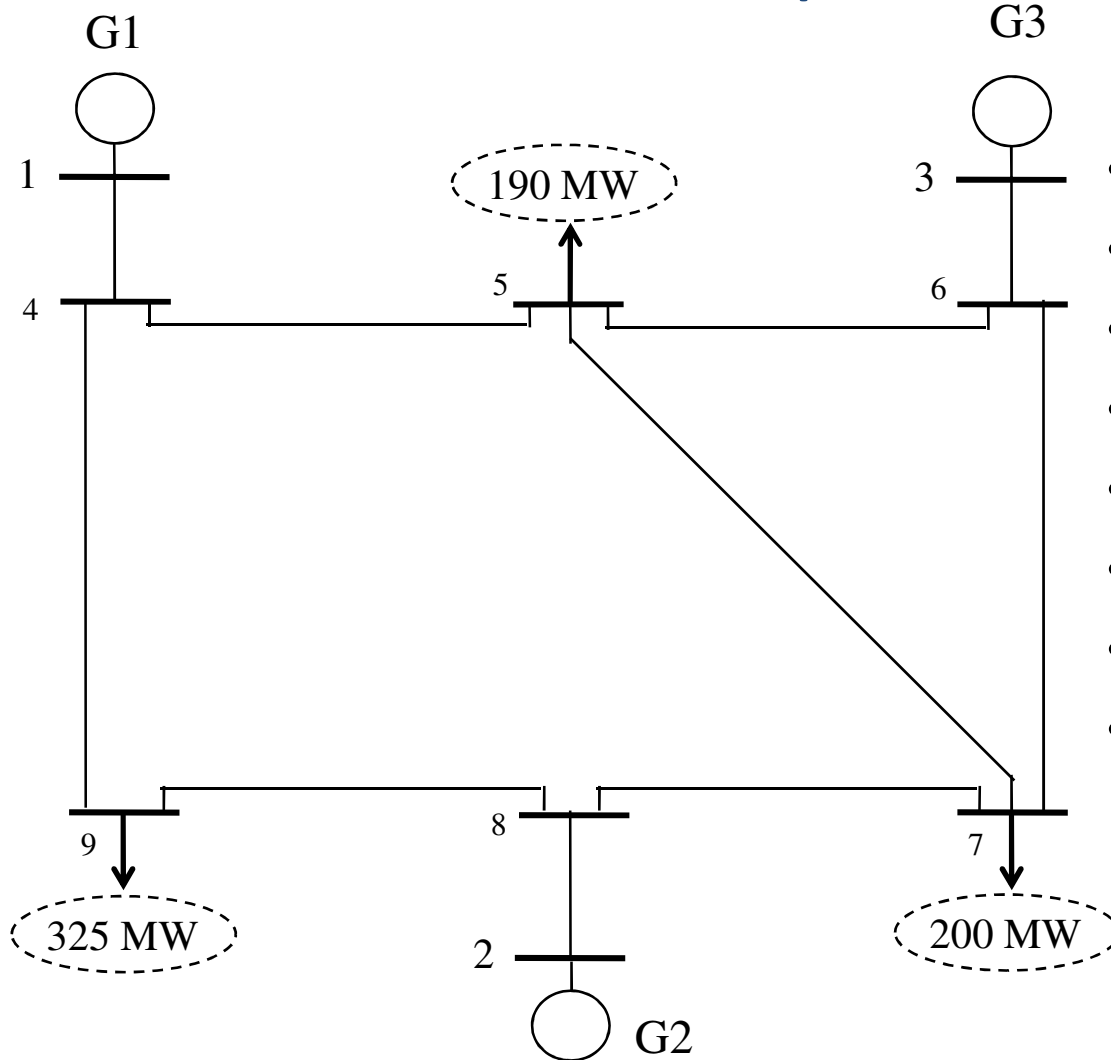


# Analytical Results

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

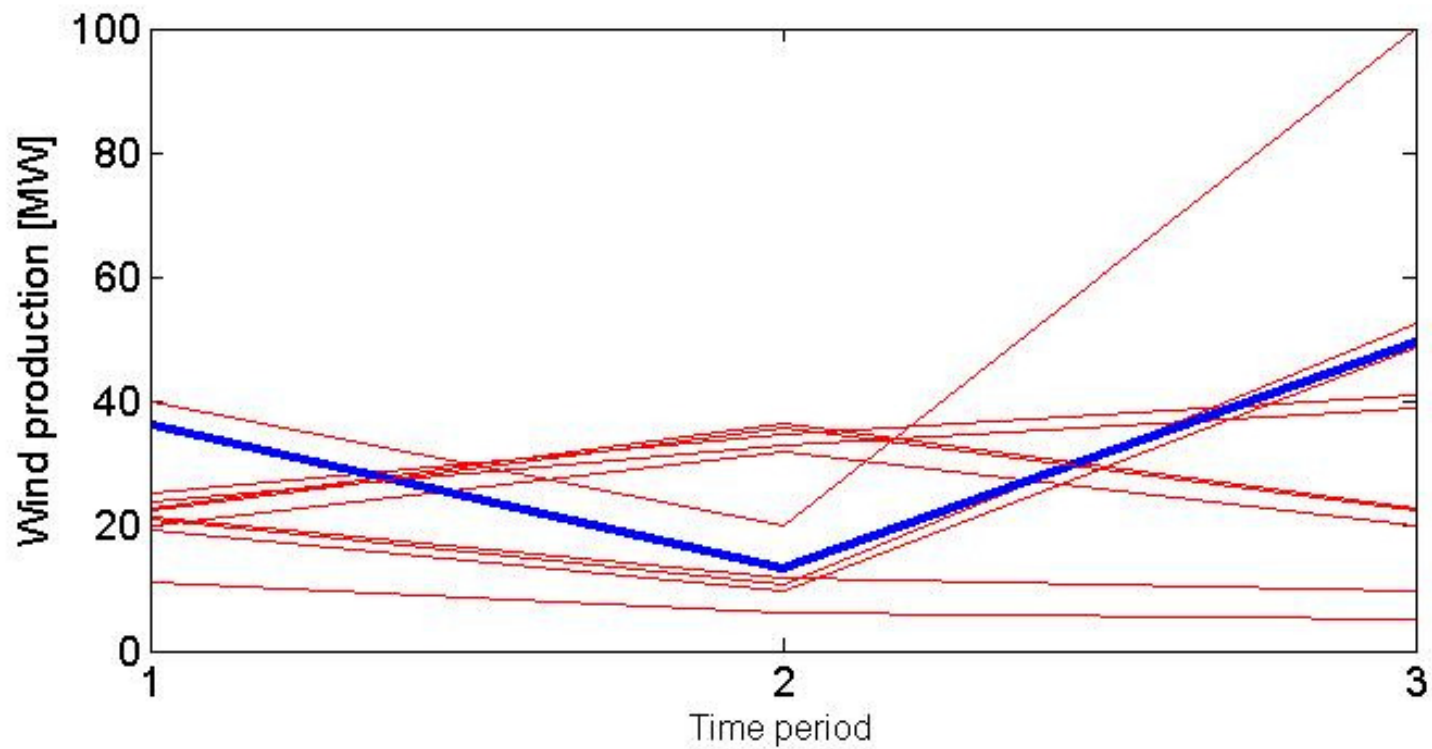
## Example: Data

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	<ul style="list-style-type: none"><li>• No DR</li><li>• 3 slow units</li><li>• <u>No fast unit</u></li></ul>	<ul style="list-style-type: none"><li>• No DR</li><li>• 3 slow and 1 fast units</li></ul>	<ul style="list-style-type: none"><li>• With DR</li><li>• 3 slow and 1 fast units</li></ul>
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?

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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!