Value of Flexible Resources, Virtual Bidding, and Self-Scheduling in Two-Settlement Electricity Markets With Wind Generation

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Research Questions

- What is the cost of wind uncertainty and the value of flexibility, given the need to commit DA in the face of forecast uncertainty?

- Do we need the system operator to do stochastic unit commitment -- or can some market players attain the least-cost solution on their own?

Two-Stage Settlement, 1 Day Horizon

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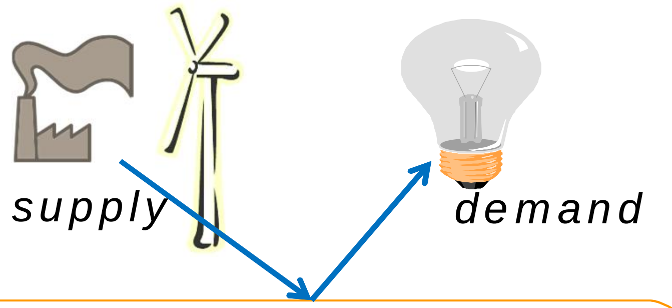
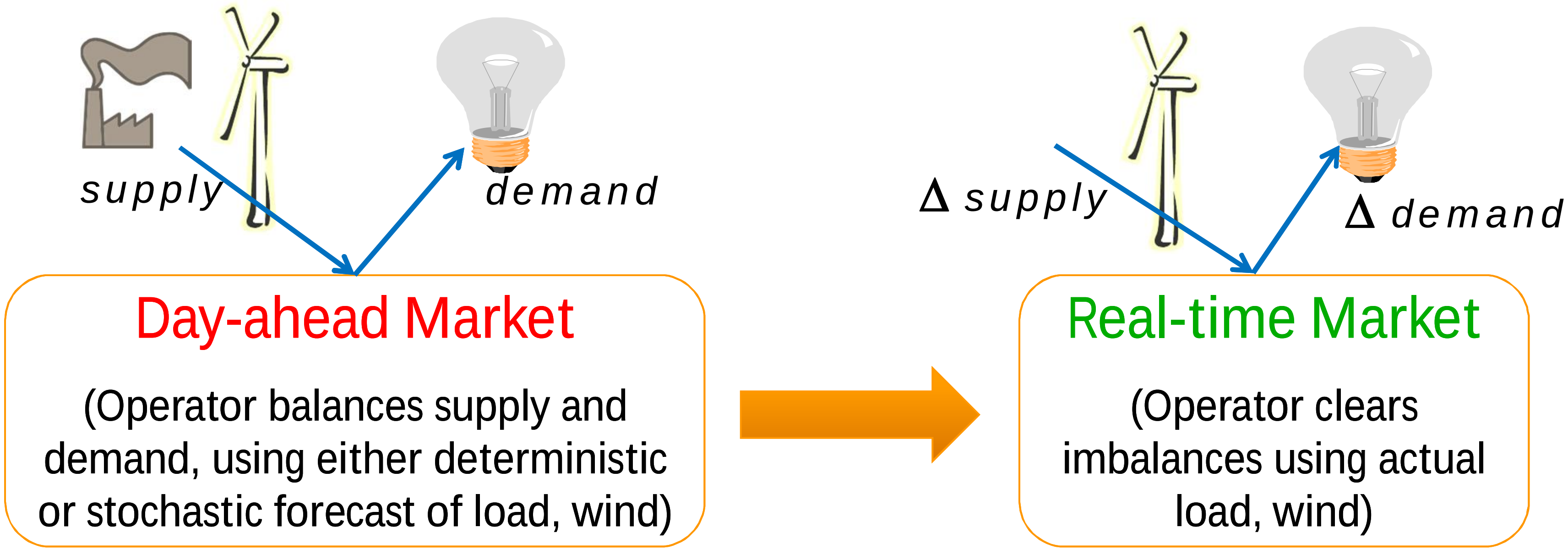


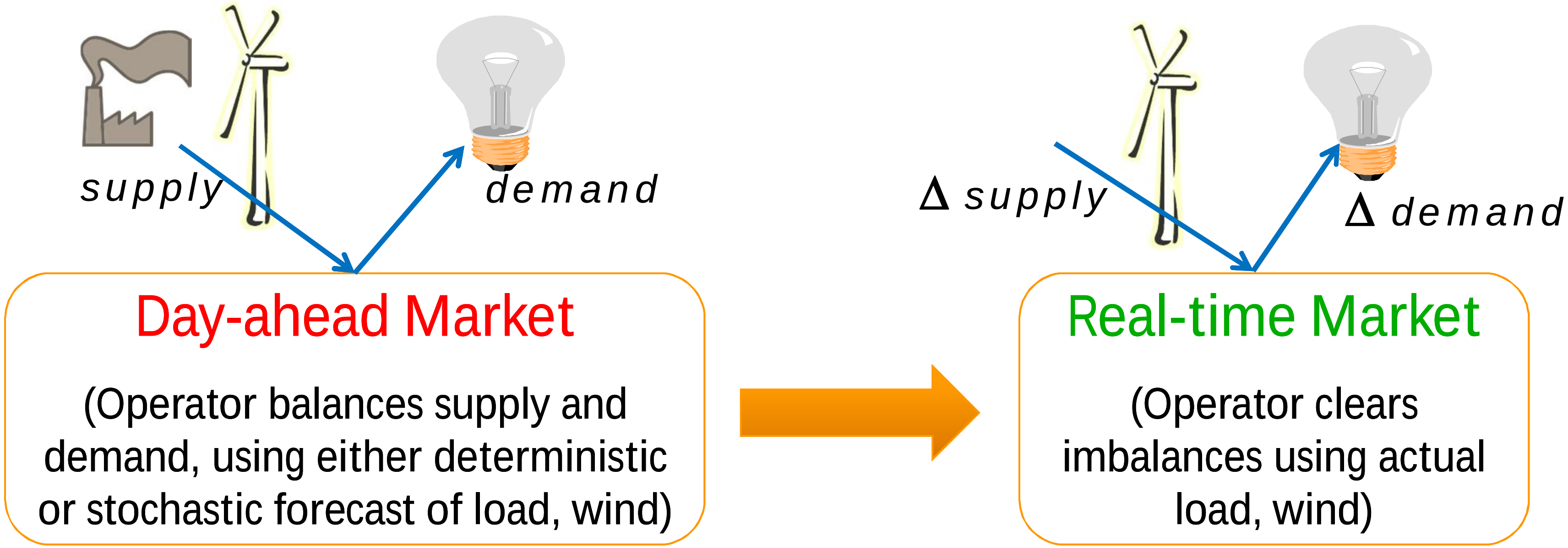
Day-ahead Market

(Operator balances supply and demand, using either deterministic or stochastic forecast of load, wind)

Two-Stage Settlement, 1 Day Horizon



Two-Stage Settlement, 1 Day Horizon



Generators:

- Slow generators commitment (*u*)
- Fast generators *tentative* commitment (*u*)
- Generator energy *tentative* (*p*)

Demand Response (DR):

- Slow DR (*d*)
- Fast DR *tentative* (*d*)

Virtual Bidders (Arbitragers):

- Virtual bidder buys/sells (+*v*)

Two-Stage Settlement, 1 Day Horizon

Day-ahead Market

(Operator balances supply and demand, using either deterministic or stochastic forecast of load, wind)

→

Real-time Market

(Operator clears imbalances using actual load, wind)

Generators:

- Slow generators commitment (*u*)
- Fast generators *tentative* commitment (*u*) → Fast generator *revised* commitment: (Δ*u*)
- Generator energy *tentative* (*p*) → Generator energy *revised* (Δ*p*)

Demand Response (DR):

- Slow DR (*d*)
- Fast DR *tentative* (*d*) → Fast DR *revised* (Δ*d*)

Virtual Bidders (Arbitragers):

- Virtual bidder buys/sells (+*v*) → Bidder sells/buys (-*v*)

Alternative Market Equilibrium Models

Two Equilibrium Models

Model 1) Social Optimum (ideal)

Total expected cost minimization:

Min [cost in DA]
+ [expected cost in RT]

Model 2) 2-stage settlement equilibrium with virtual bidders

2-stage settlement equilibrium model:

DA market: Min [cost in DA]

Each virtual bidder: Max E(profit)

RT market for each wind scenario: Min [cost in RT]

Alternative Market Equilibrium Models

Two Equilibrium Models

Model 1) Social Optimum (ideal)

- The TSO solves a single *stochastic* optimization problem, considering DA and RT markets simultaneously,
- Objective: MIN total E(cost),
- Equivalent to competitive self-scheduling equilibrium.

Total expected cost minimization:

Min [cost in DA]
+ [expected cost in RT]

Model 2) 2-stage settlement equilibrium with virtual bidders

- First the TSO clears the DA market using *deterministic* forecast, then clears the RT market,
- Each stage's optimization is a deterministic problem assuming all gen and DR bid truthfully; no self-scheduling,
- Virtual bidders consider both markets simultaneously, only they know the actual distribution.

2-stage settlement equilibrium model:

DA market: Min [cost in DA]

Each virtual bidder: Max E(profit)

RT market for each wind scenario: Min [cost in RT]

Model 3) Extended Version of Model 2: Two-stage settlement equilibrium model with Self-Scheduling Slow Generators:

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Extended 2-stage settlement equilibrium model:

DA market:

Min [cost in DA] excluding the cost of self-scheduling slow generators

RT market for each wind scenario:

Min [cost in RT] excluding the cost of self-scheduling slow generators

Each virtual bidder:

Max E(profit)

Each self-scheduling slow generator:

Max E(profit)

Solution Techniques

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

- Equilibrium models are solved by considering the KKT conditions of all optimization problems simultaneously.

Illustrative Example: Single-Node Case

- Two slow conventional generators: G1 and G2
- One fast conventional generators: G3
- A single wind power producer: WP
- A single inelastic load
- A virtual bidder: VB

Illustrative Example: Single-Node Case

➢ Technical characteristics of conventional generators:

Gen.	Type	Pmin [MW]	Pmax [MW]	Ramp [MW/h]	Marginal Cost [$/MWh]	Start-up cost [$]
G1	Slow	1000	1000	1000	50	15,000
G2	Slow	0	1000	1000	60	10,000
G3	Fast	0	500	500	120	1000

Illustrative Example: Single-Node Case

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- Wind power forecast:
  - In DA stage: 250 MW
  - In RT stage, scenario 1: 0 MW (probability: 0.5)
  - In RT stage, scenario 2: 500 MW (probability: 0.5)
- Load: 1000 MW

Illustrative Example: Results

Market equilibrium model	Total expected system cost [$]
Model 1 (stochastic ideal solution)	47,500

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Market equilibrium model	Total expected system cost [$]
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- Generator G3 (fast unit, but expensive) is not committed (always off).
- Generator G2 (slow unit) is committed appropriately in DA, and manages all power imbalances in RT.

Illustrative Example: Results

Market equilibrium model	Total expected system cost [$]
Model 1 (stochastic ideal solution)	47,500
Model 2 (sequential DA-RT) without virtual bidding	56,500

Illustrative Example: Results

Market equilibrium model	Total expected system cost [$]
Model 1 (stochastic ideal solution)	47,500
Model 2 (sequential DA-RT) without virtual bidding	56,500

- Cost of uncertainty: $9000 [$56,500 – $47,500]
- Flexible resources can reduce the cost of uncertainty.
- In Model 2, fast generator G3 is committed in RT, because slow generator G2 is not committed in DA (wrong dispatch).

Illustrative Example: Results

Market equilibrium model	Total expected system cost [$]
Model 1 (stochastic ideal solution)	47,500
Model 2 (sequential DA-RT) without virtual bidding	56,500
Model 2 (sequential DA-RT) with virtual bidding	55,000

Illustrative Example: Results

Market equilibrium model	Total expected system cost [$]
Model 1 (stochastic ideal solution)	47,500
Model 2 (sequential DA-RT) without virtual bidding	56,500
Model 2 (sequential DA-RT) with virtual bidding	55,000

- Virtual bidding reduces the cost on uncertainty, but the system cost is still different than the ideal solution.
- The virtual bidder buys 250 MW in DA, and sells it back in RT. The fast generator G3 is always off, but the DA dispatch of slow generator G2 is still wrong!

Illustrative Example: Results

Market equilibrium model	Total expected system cost [$]
Model 1 (stochastic ideal solution)	47,500
Model 2 (sequential DA-RT) without virtual bidding	56,500
Model 2 (sequential DA-RT) with virtual bidding	55,000
Model 3 (extended Model 2) with virtual bidding, while generator G2 self-schedules	47,500

Illustrative Example: Results

Market equilibrium model	Total expected system cost [$]
Model 1 (stochastic ideal solution)	47,500
Model 2 (sequential DA-RT) without virtual bidding	56,500
Model 2 (sequential DA-RT) with virtual bidding	55,000
Model 3 (extended Model 2) with virtual bidding, while generator G2 self-schedules	47,500

- In this case, virtual bidding together with self-scheduling by a slow generator, can enable a deterministic DA market to choose the most efficient unit commitment.

Conclusions

- We present different stochastic and deterministic two-stage (DA-RT) market designs, including virtual bidding and self-scheduling generators.
- A comparison of different market designs enables us to derive the cost of uncertainty and the value of flexible resources.
- The market operator may not need to do a stochastic DA unit commitment.
- Virtual bidding together with self-scheduling by slow generator(s) may enable a deterministic DA market to choose the most efficient unit commitment.

Reference

J. Kazempour and B. F. Hobbs, “Value of flexible resources, virtual bidding, and self-scheduling in two-settlement electricity markets with wind generation," (a two-part paper), *submitted*, 2016.

Thanks for your attention!

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