Electricity Market Clearing With Improved Scheduling of Stochastic Production

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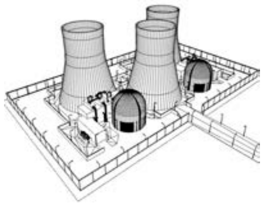
Motivation

DAY-AHEAD MARKET

BALANCING MARKET



Time

Day d-1

Day d

Day-ahead dispatch

CONVENTIONAL | STOCHASTIC | IMPROVED

DAY-AHEAD (MERIT-ORDER) → BALANCING

Conventional (model)

DAY-AHEAD

$$\underset{p_G, p_W, \delta^0}{\text{Minimize}} \quad C^D(p_G, p_W)$$ → Day-ahead dispatch costs

$$\text{s.t.} \quad h^D(p_G, p_W, \delta^0) - l = 0$$ → Power balance at the day-ahead stage

$$g^D(p_G, \delta^0) \le 0$$ → Technical limits at the day-ahead stage

$$p_W \le \hat{W}$$ → Typically the expected production!

$$p_G^*, p_W^*, \delta^{0*}$$

BALANCING

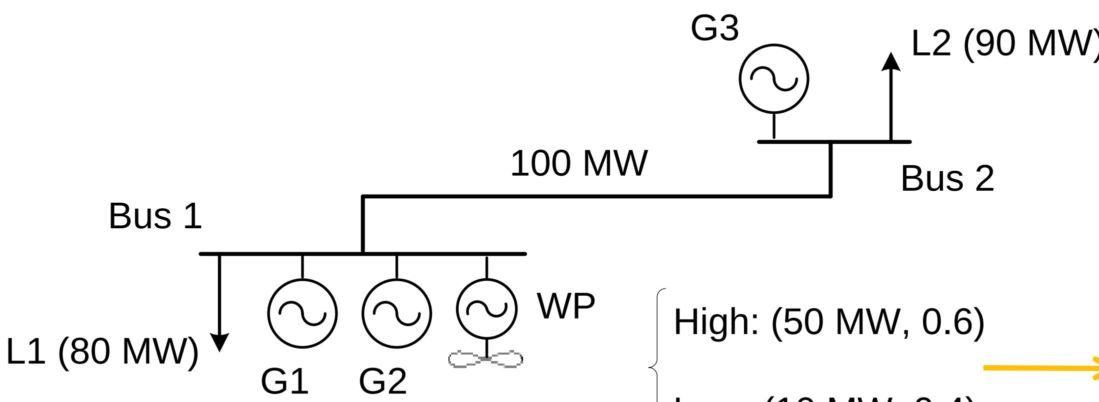
$$\underset{y_{\omega'}}{\text{Minimize}} \quad C^B(y_{\omega'})$$ → Balancing dispatch costs

$$\text{s.t.} \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p_W^* = 0$$ → Power balance at the balancing stage

$$g^B(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}) \le 0$$ → Technical limits at the balancing stage

$$P_i^* - r_{i\omega}^{\mathrm{D}} \ge 0, \forall i, \forall \omega$$
$$P_i^* + r_{i\omega}^{\mathrm{U}} \le \overline{P}_i, \forall i, \forall \omega$$

Conventional (example)



High: (50 MW, 0.6)

Low: (10 MW, 0.4)

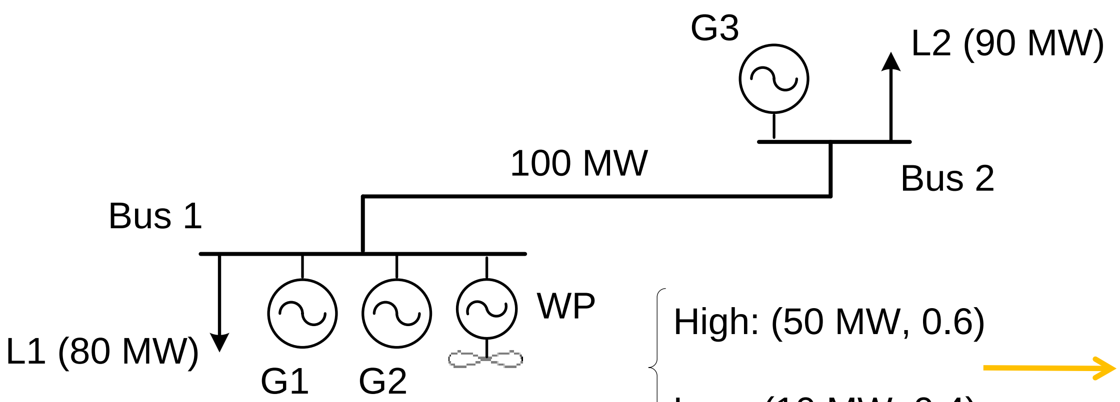
→ Exp. production = 34 MW

	DAY-AHEAD		BALANCING			
Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0
WP	34	0	–	–	0	0

- G1 → Expensive, but flexible
- G2 → Less expensive, but inflexible
- G3 → Cheap, but inflexible
- WP → Free, but uncertain

Powers in MW; costs in $/MWh

Conventional (example)



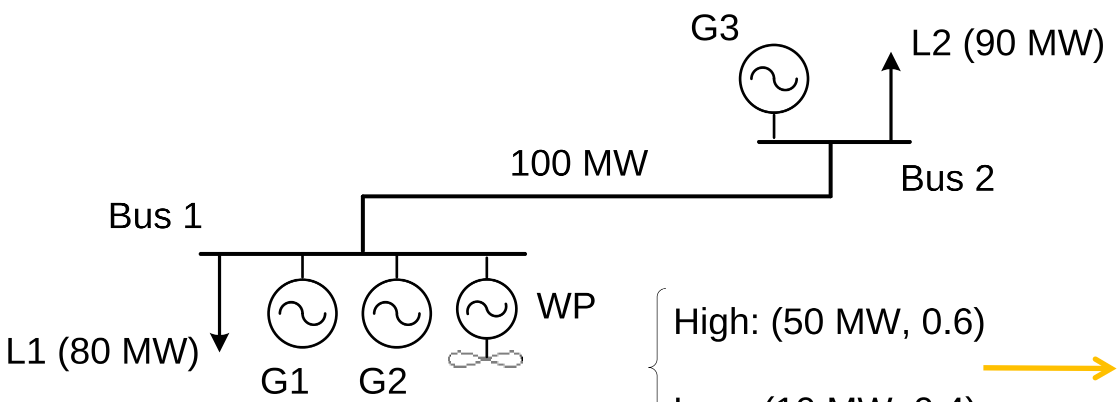
High: (50 MW, 0.6)
Low: (10 MW, 0.4)

Exp. production = 34 MW

	DAY-AHEAD DISPATCH		
Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Cost merit-order

Conventional (example)



High: (50 MW, 0.6)

Low: (10 MW, 0.4)

Exp. production = 34 MW

	DAY-AHEAD DISPATCH			BALANCING				HIGH (+16MW)		LOW (-24MW)	
Unit	$P^{\max}$	C	P^{sch}	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$	$r_{i\omega}^{U}$	$r_{i\omega}^{D}$	$r_{i\omega}^{U}$	$r_{i\omega}^{D}$
G1	100	35	0	40	34	20	40	0	0	20	0
G2	110	30	86	–	–	0	0	0	0	0	0
G3	50	10	50	–	–	0	0	0	0	0	0
WP	34	0	34	–	–	0	0	0	16	0	0
	DACOST = $3080							BCOST = $0		BCOST = $1600	

TOTAL COST = $3720

Day-ahead dispatch

CONVENTIONAL STOCHASTIC IMPROVED

- ✓ Follows merit-order
- ✓ Easy to implement

- × High balancing costs

Stochastic (model)

DAY-AHEAD

$$\underset{p_G, p_W, \delta^0; y_\omega, \forall\omega}{Minimize} \; C^D(p_G, p_W) + \boxed{\mathrm{E}_\omega\left[C^B(y_\omega)\right]}$$

$$\begin{aligned}
s.t. \quad & h^D(p_G, p_W, \delta^0) - l = 0 \\
& g^D(p_G, \delta^0) \le 0 \\
& p_W \le \overline{W} \\
& h^B(y_\omega, \delta_\omega, \delta^0) + W_\omega - p_W = 0, \quad \forall\omega \\
& g^B(y_\omega, \delta_\omega, p_G; W_\omega) \le 0, \quad \forall\omega
\end{aligned}$$

Balancing prognosis

(Two-stage stochastic programming)

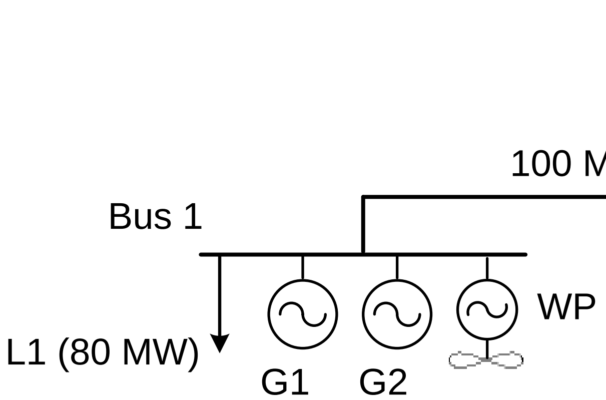
$$\Big\downarrow \; p_G^*, p_W^*, \delta^{0*}$$

BALANCING

$$\underset{y_{\omega'}}{Minimize} \quad C^B(y_{\omega'})$$

$$\begin{aligned}
s.t. \quad & h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p_W^* = 0 \\
& g^B(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}) \le 0
\end{aligned}$$

Stochastic (example)



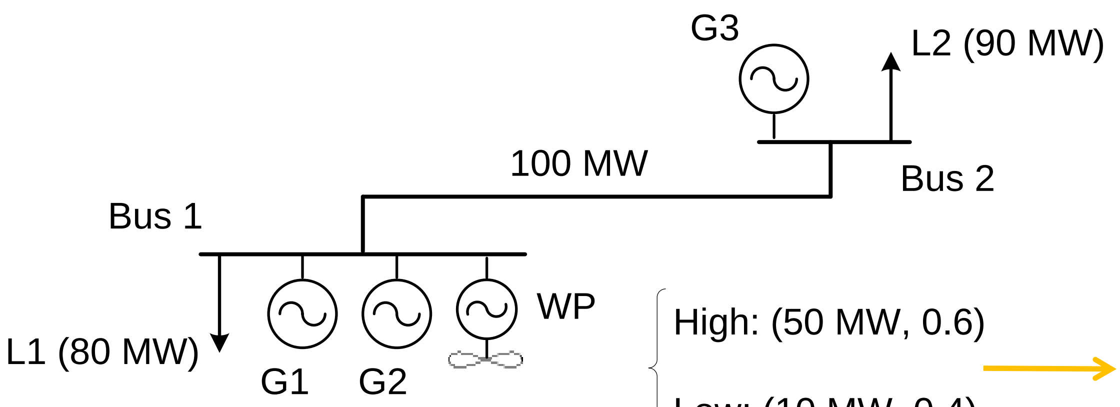
High: (50 MW, 0.6)
Low: (10 MW, 0.4)

→ Exp. production = 34 MW

	Day-ahead dispatch		
Unit	$P^{\max}$	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

- G1 → To exploit ability to reduce production
- G2 → Less expensive, but inflexible
- G3 → Cheap, but flexible
- WP → Dispatched below expected production

Stochastic (example)



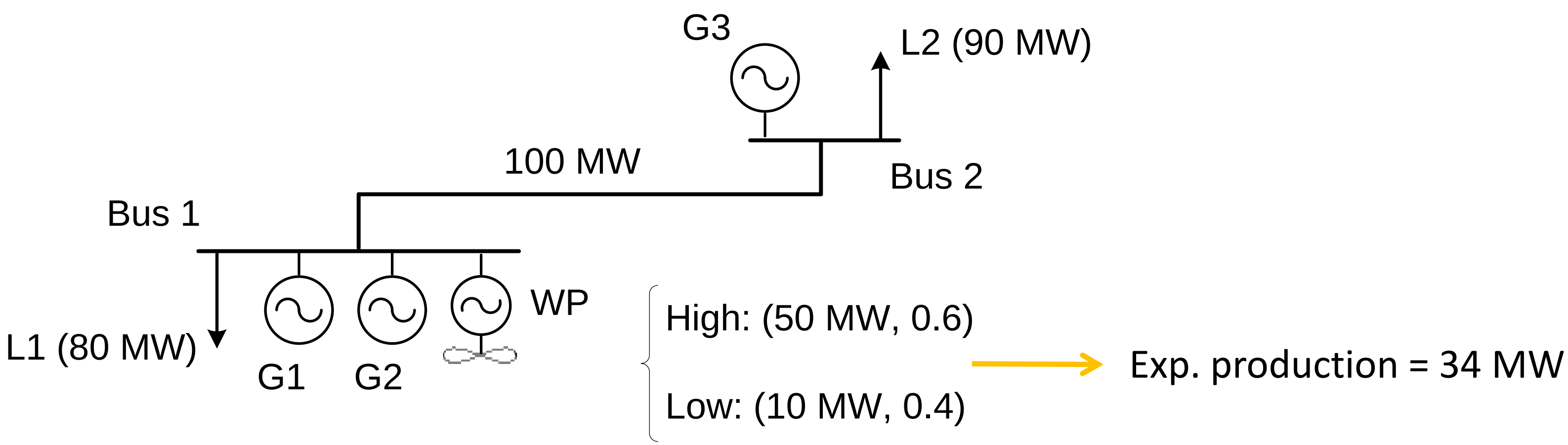
High: (50 MW, 0.6)
Low: (10 MW, 0.4)

→ Exp. production = 34 MW

	Day-ahead dispatch		
Unit	$P^{\max}$	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

~~Cost merit-order~~

Stochastic (example)



	Day-ahead dispatch			Balancing				High (+40MW)		Low (0MW)	
Unit	$P^{\max}$	C	P^{sch}	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$	$r_{i\omega}^{U}$	$r_{i\omega}^{D}$	$r_{i\omega}^{U}$	$r_{i\omega}^{D}$
G1	100	35	40	40	34	20	40	0	40	0	0
G2	110	30	70	–	–	0	0	0	0	0	0
G3	50	10	50	–	–	0	0	0	0	0	0
WP	34	0	10	–	–	0	0	0	0	0	0
	DAcost = $4000							Bcost = -$1360		Bcost = $0	

Total Cost = $3184

Comparison

	Conv	Stoc
Day-ahead dispatch cost ($)	3080	4000
Expected re-dispatch cost ($)	640	-816
Total cost ($)	3720	3184

Stochastic day-ahead dispatch yields a lower total cost!!

What about the profits of the units?

Comparison

Conventional

Day-ahead

$$\underset{p_G, p_W, \delta^0}{\text{Minimize}} \quad C^D(p_G, p_W)$$
$$\text{s.t.} \quad h^D(p_G, p_W, \delta^0) - l = 0 : \boxed{\lambda^D}$$
$$g^D(p_G, \delta^0) \le 0$$
$$p_W \le \hat{W}$$

$$\downarrow \; p_G^*, p_W^*, \delta^{0*}$$

Balancing

$$\underset{y_{\omega'}}{\text{Minimize}} \quad C^B(y_{\omega'})$$
$$\text{s.t.} \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p_W^* = 0 : \boxed{\lambda^B_{\omega'}}$$
$$g^B(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}) \le 0$$

Stochastic

Day-ahead

$$\underset{p_G, p_W, \delta^0; y_\omega, \forall\omega}{\text{Minimize}} \quad C^D(p_G, p_W) + \mathrm{E}_\omega\left[C^B(y_\omega)\right]$$
$$\text{s.t.} \quad h^D(p_G, p_W, \delta^0) - l = 0 : \boxed{\lambda^D}$$
$$g^D(p_G, \delta^0) \le 0$$
$$p_W \le \overline{W}$$
$$h^B(y_\omega, \delta_\omega, \delta^0) + W_\omega - p_W = 0, \quad \forall\omega$$
$$g^B(y_\omega, \delta_\omega, p_G; W_\omega) \le 0, \quad \forall\omega$$

$$\downarrow \; p_G^*, p_W^*, \delta^{0*}$$

Balancing

$$\underset{y_{\omega'}}{\text{Minimize}} \quad C^B(y_{\omega'})$$
$$\text{s.t.} \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p_W^* = 0 : \boxed{\lambda^B_{\omega'}}$$
$$g^B(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}) \le 0$$

Comparison

	Conv	Stoc
Day-ahead dispatch cost ($)	3080	4000
Expected re-dispatch cost ($)	640	-816
Total cost ($)	3720	3184

	Conv	Stoc
Day-ahead price ($/MWh)	30/30	30/30
G1 profit for high wind ($)	0	173,3
G1 profit for low wind ($)	3300	$\boxed{-200}$
G1 expected profit ($)	1320	24

	Day-ahead	
Unit	$P^{\max}$	C
G1	100	35
G2	110	30
G3	50	10

In the stochastic market clearing unit G1 is dispatched day ahead in a **loss-making position**

Day-ahead dispatch

Conventional

Day-ahead (Merit-order) → Balancing

- ✓ Follows merit-order
- ✓ Easy to implement

- × High balancing costs

Stochastic

Day-ahead (Two-stage) → Balancing

- ✓ Reduce expected cost

- × Dispatch units in a loss-making position
- × Cost recovery for flexible producers only in expectation

Improved

Improved (model)

DAY-AHEAD

$$\underset{p_G,\, p_W,\, \delta^0}{\text{Minimize}} \quad C^D(p_G, p_W)$$

$$\text{s.t.} \quad h^D(p_G, p_W, \delta^0) - l = 0$$

$$g^D(p_G, \delta^0) \leq 0$$

$$\boxed{p_W \leq \hat{W}}$$

Do we have something better than the expected production?

$$\downarrow \; p_G^*, p_W^*, \delta^{0*}$$

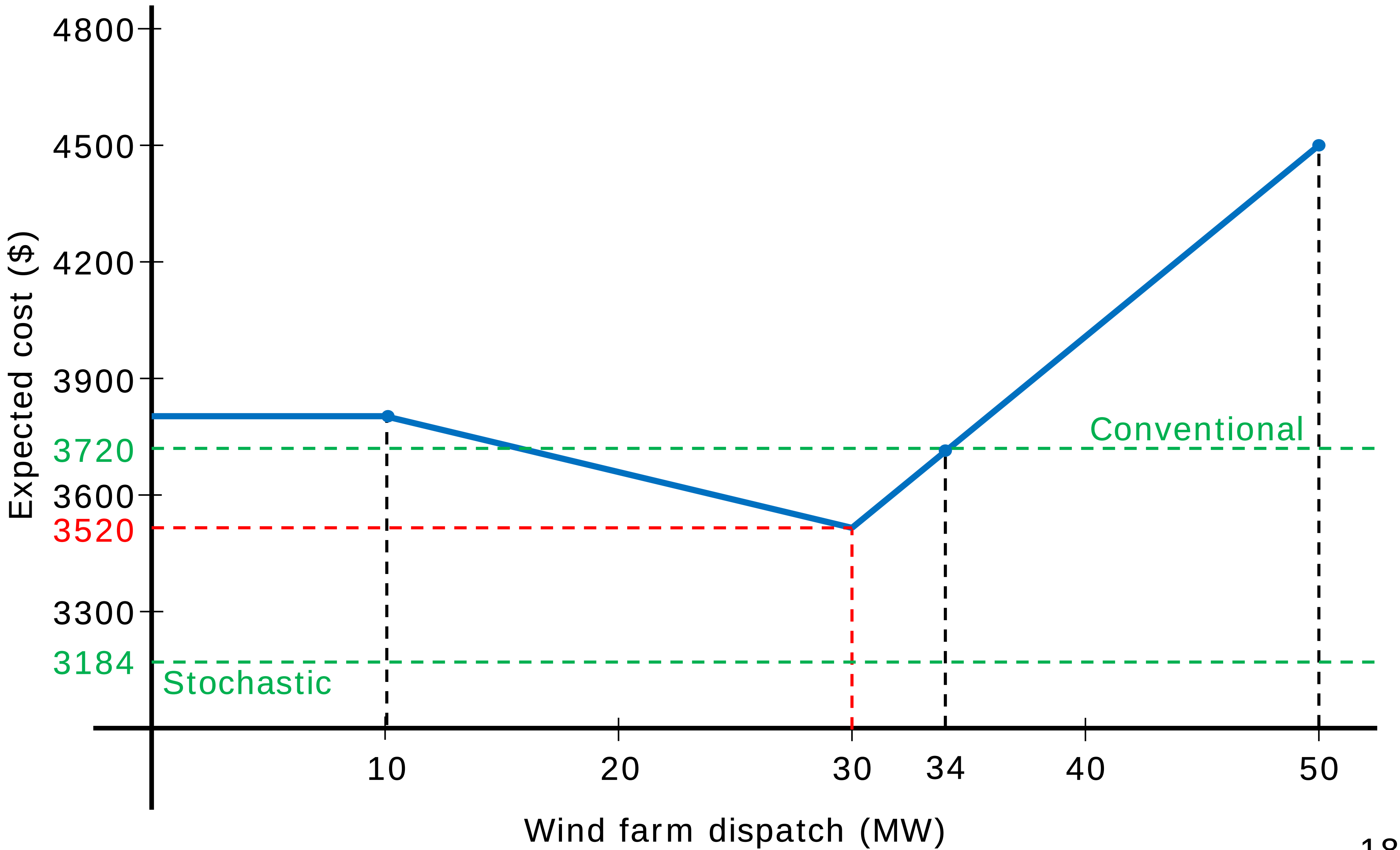
BALANCING

$$\underset{y_{\omega'}}{\text{Minimize}} \quad C^B(y_{\omega'})$$

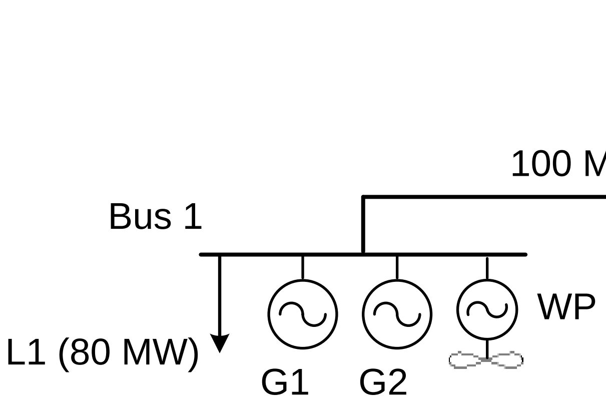
$$\text{s.t.} \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p_W^* = 0$$

$$g^B(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}) \leq 0$$

Improved (model)



Improved (example)



High: (50 MW, 0.6)
Low: (10 MW, 0.4)

→ Exp. production = 34 MW

	Day-ahead dispatch			Balancing				High (+20MW)		Low (-20MW)	
Unit	$P^{\max}$	C	P^{sch}	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$	$r_{i\omega}^{U}$	$r_{i\omega}^{D}$	$r_{i\omega}^{U}$	$r_{i\omega}^{D}$
G1	100	35	0	40	34	20	40	0	0	20	0
G2	110	30	90	–	–	0	0	0	0	0	0
G3	50	10	50	–	–	0	0	0	0	0	0
WP	34	0	30	–	–	0	0	0	20	0	0
	DAcost = $3200							Bcost = $0		Bcost = $800	

Total Cost = $3520

Comparison

	Conv	Stoc	Impr
Day-ahead dispatch cost ($)	3080	4000	3200
Expected re-dispatch cost ($)	640	-816	320
Total cost ($)	3720	3184	3520

	Conv	Stoc	Impr
Day-ahead price ($/MWh)	30/30	30/30	30/30
G1 profit for high wind ($)	0	173,3	100
G1 profit for low wind ($)	3300	-200	0
G1 expected profit ($)	1320	24	60

Dispatching the wind to 30 MW reduces the total cost while ensuring a positive profit of unit G1 for all scenarios

Improved (model)

DAY-AHEAD

$$
\begin{aligned}
&\underset{p_G, p_W, \delta^0, \boxed{p_W^{\max}}; y_\omega, \delta_\omega, \forall\omega}{\text{Minimize}} \quad C^D(p_G, p_W) + \boxed{\mathrm{E}_\omega\left[C^B(y_\omega)\right]} \\
&\text{s.t.} \quad h^B(y_\omega, \delta_\omega, \delta^0) + W_\omega - p_W = 0, \quad \forall\omega \\
&\qquad g^B(y_\omega, \delta_\omega, p_G; W_\omega) \le 0, \quad \forall\omega \\
&\qquad 0 \le p_W^{\max} \le \overline{W} \\
&\qquad (p_G, p_W, \delta^0) \in \arg\Big\{ \underset{x_G, x_W, \theta}{\text{Minimize}} \quad C^D(x_G, x_W) \\
&\qquad\qquad\qquad \text{s.t.} \quad h^D(x_G, x_W, \theta) - l = 0 \\
&\qquad\qquad\qquad\qquad g^D(x_G, \theta) \le 0 \\
&\qquad\qquad\qquad\qquad x_W \le \boxed{p_W^{\max}} \Big\}
\end{aligned}
$$

$$p_G^*, p_W^*, \delta^{0*}$$

BALANCING

$$
\begin{aligned}
&\underset{y_{\omega'}}{\text{Minimize}} \quad C^B(y_{\omega'}) \\
&\text{s.t.} \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p_W^* = 0 \\
&\qquad g^B(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}) \le 0
\end{aligned}
$$

Bilevel optimization problem

The “marginal cost” of a stochastic generator is the cost of its uncertainty

Day-ahead dispatch

Conventional

Day-ahead (Merit-order) → Balancing

- ✓ Follows merit-order
- ✓ Easy to implement

- × High balancing costs

Stochastic

Day-ahead (Two-stage) → Balancing

- ✓ Reduce expected cost

- × Dispatch units in a loss-making position
- × Cost recovery for flexible producers only in expectation

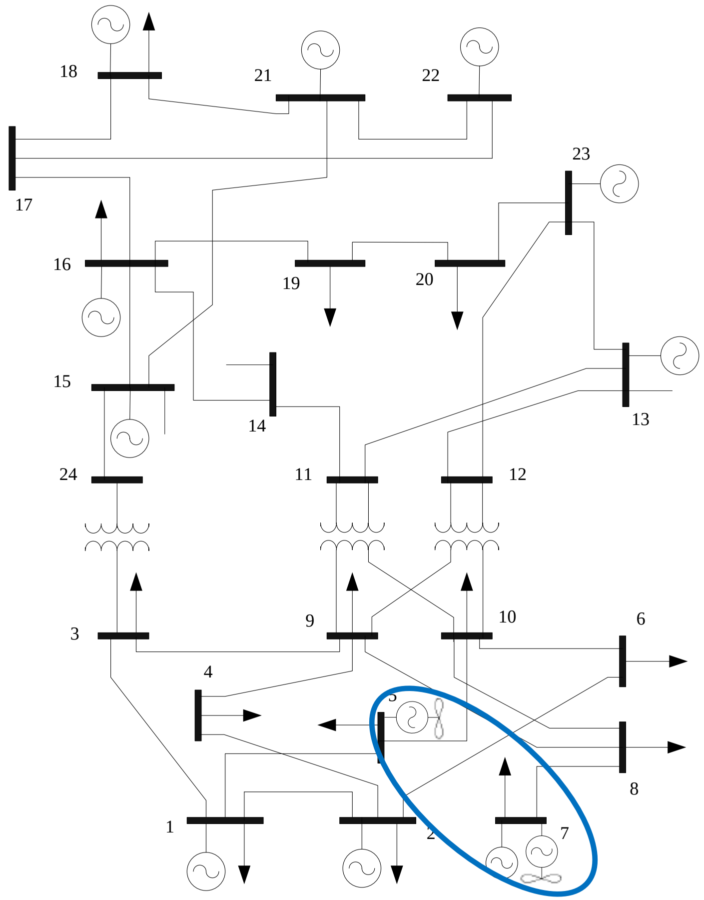
Improved

Day-ahead (Bilevel) → Balancing

- ✓ Lowest expected cost following merit-order
- ✓ Cost recovery for scenario

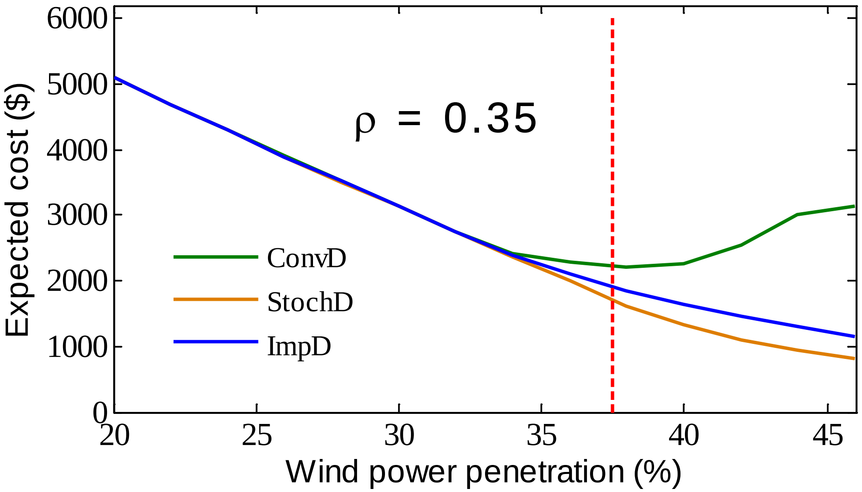
- × High computational burden

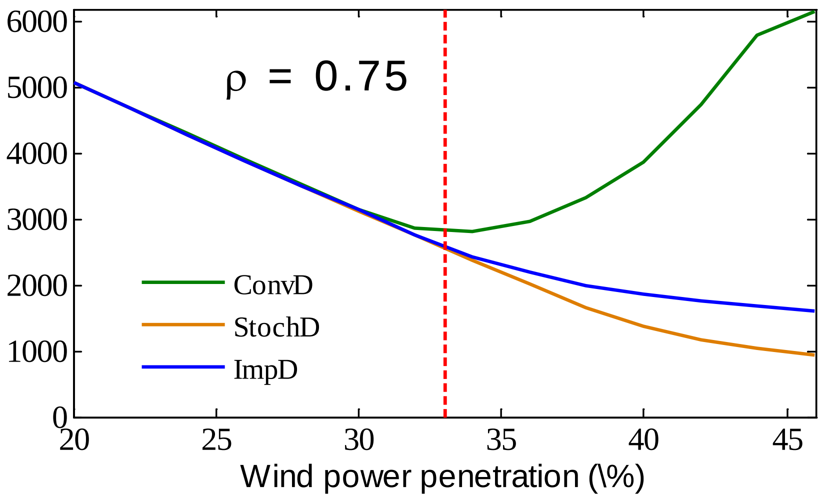
24-bus case study



- Based on the IEEE Reliability test System
- Total system demand = 2000 MW
- Per-unit wind power productions are modeled using Beta distributions with a correlation coefficient ρ

24-bus case study





- Under "ImpD" and "StochD", higher penetrations of stochastic production never lead to an increase in the expected cost

- "ImpD" and "StochD" are robust to the spatial correlation of stochastic energy sources

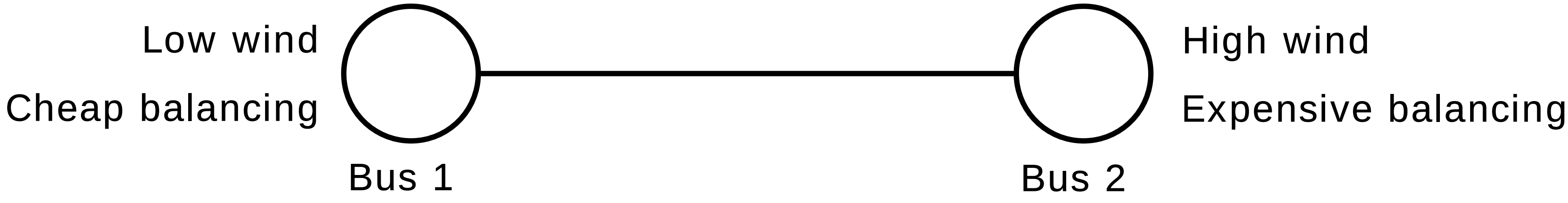
24-bus case study

Wind penetration 38% $\rho = 0.35$		Unit			
		G1	G6	G11	G12
Stoch	Expected profit ($)	47.9	49.4	102.2	67.4
	Avearge losses ($)	–14.9	–10.7	–16.5	–9.7
	Probability profit < 0	**0.81**	0.71	0.71	0.75
Conv	Expected profit ($)	379.8	359.7	724.9	389.1
Imp	Expected profit ($)	170.2	263.7	531.6	178.7

Conclusions

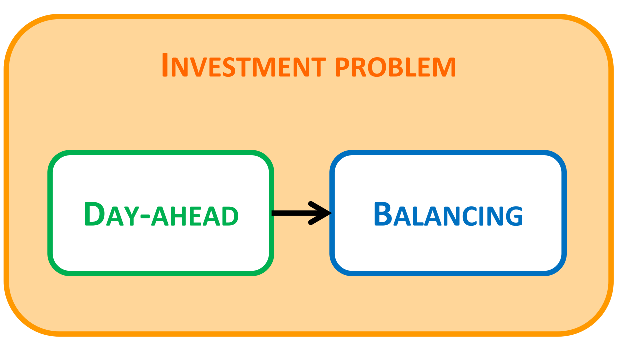
- Day-ahead markets should not clear the expected stochastic production by default.
- The amount of stochastic generation to be scheduled in advance should not be driven only by its marginal cost, which is usually very low or zero, but also by the **cost of its uncertainty**.
- The "improved dispatch" substantially increases market efficiency and mimics the advantageous features of the stochastic ideal, while guaranteeing cost recovery **for any realization of the stochastic production**.

Current work

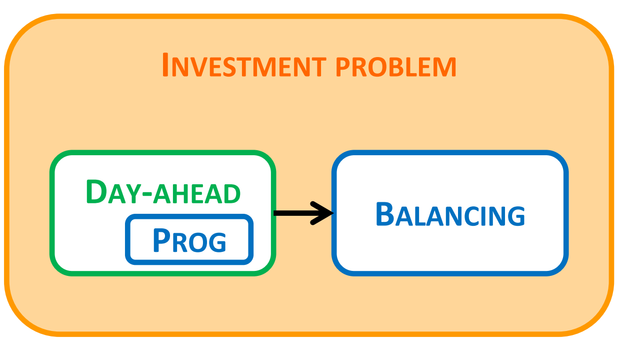


- Where should I locate wind farms?
- Can the market clearing impact my investment decisions

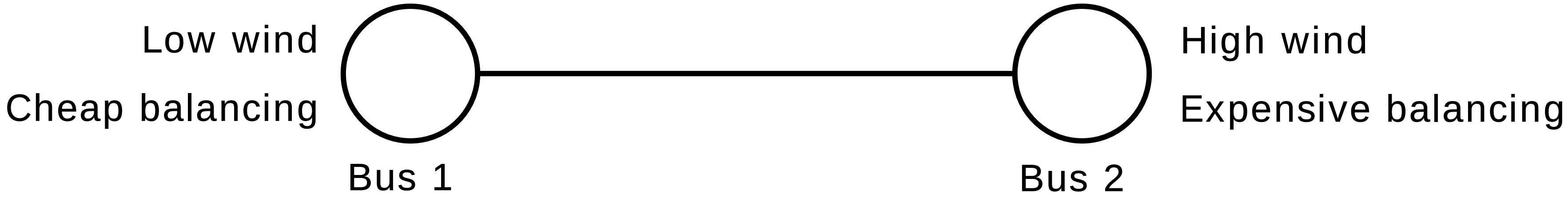
CONVENTIONAL

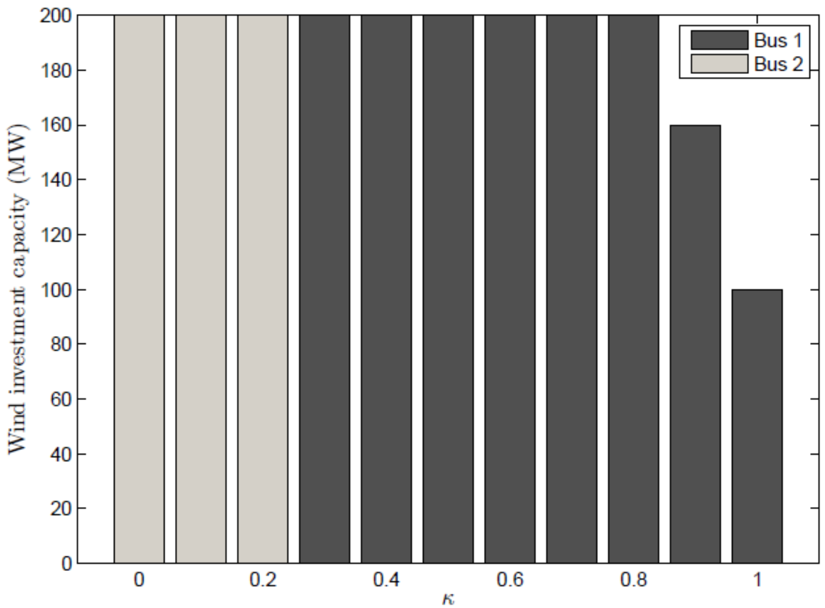


STOCHASTIC



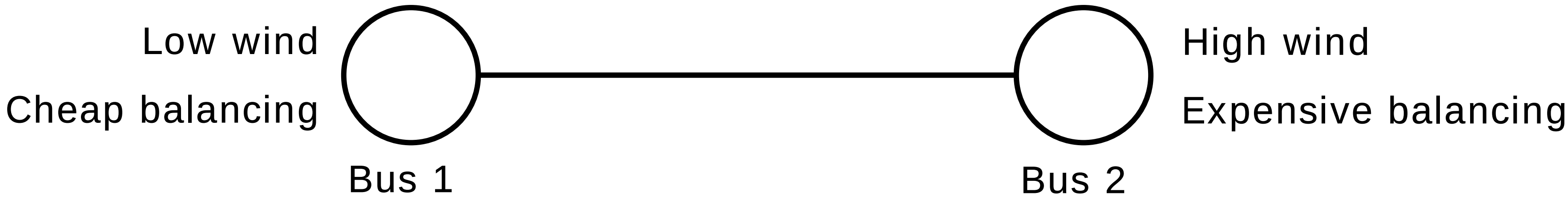
Current work

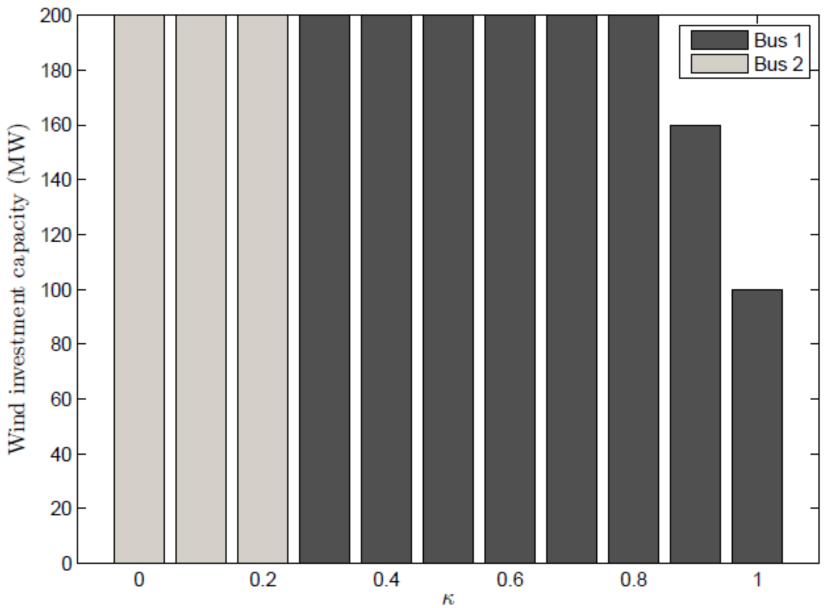




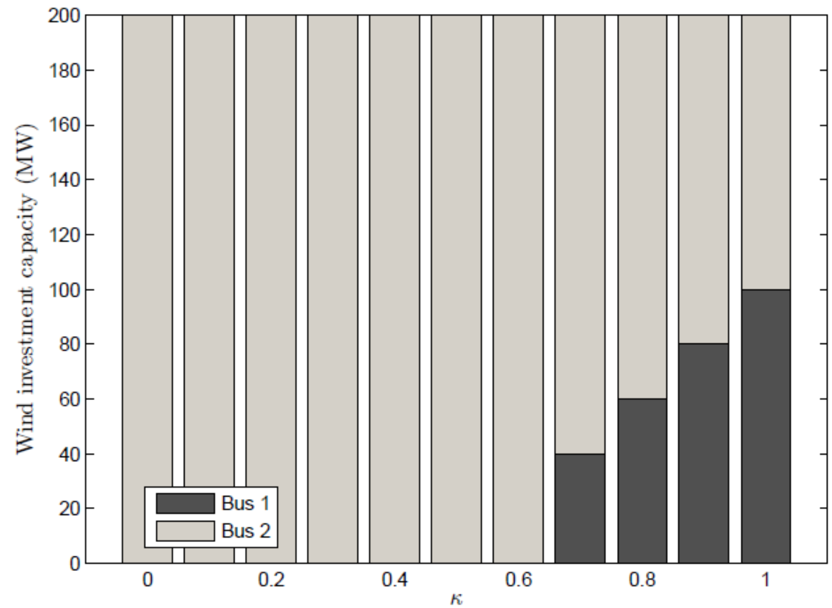
(a) ConvMC

Current work

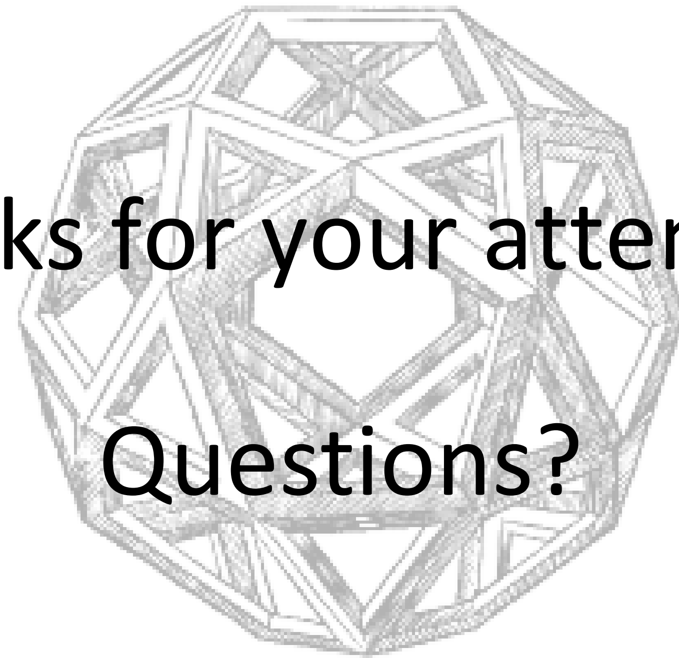




(a) ConvMC



(b) StocMC



Thanks for your attention!

Questions?