Mechanisms to Increase the Efficiency of Two-stage Electricity Markets with Uncertain Supply

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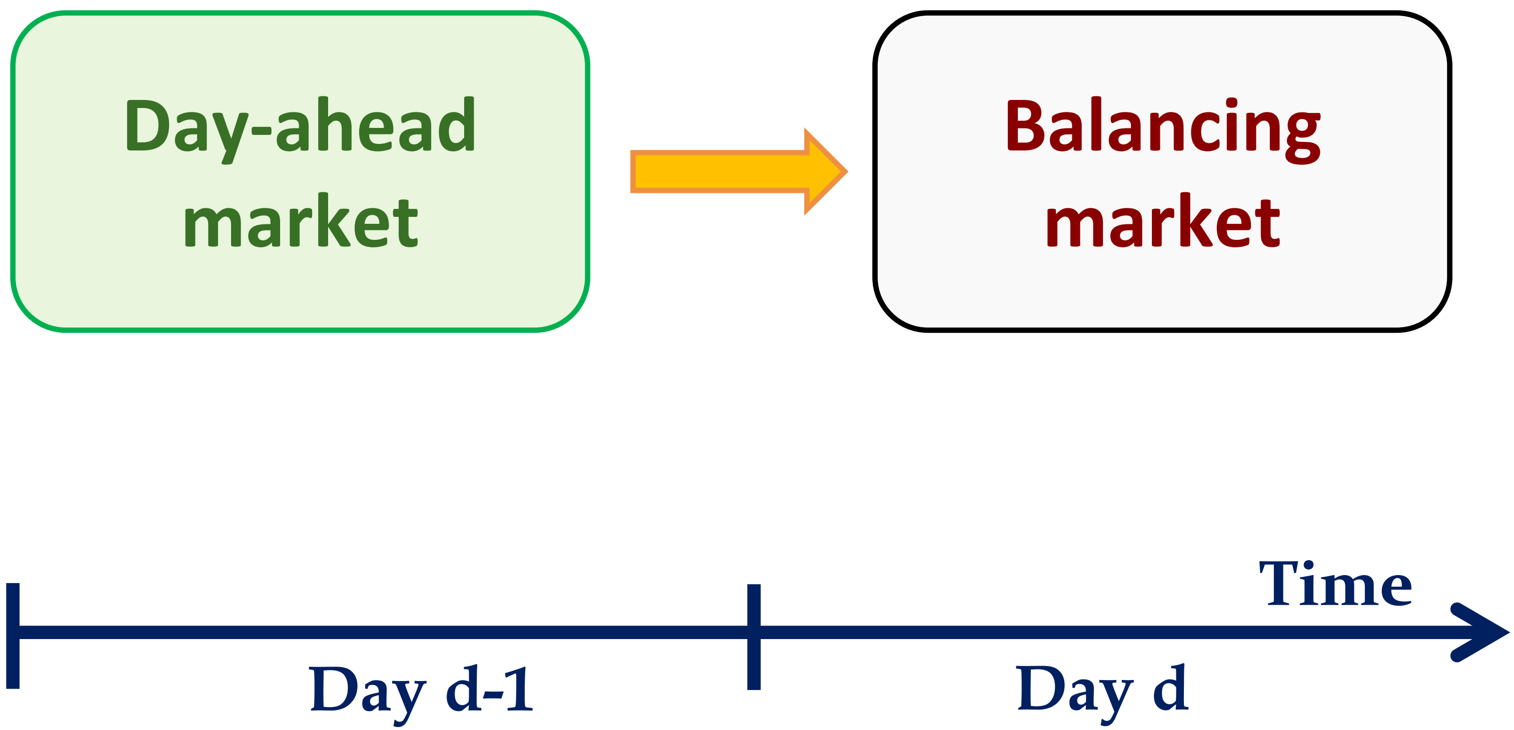
Outline

1. Basic structure of short-term electricity markets
2. Problem statement
3. Dealing with uncertain supply: market mechanisms
4. Concluding remarks

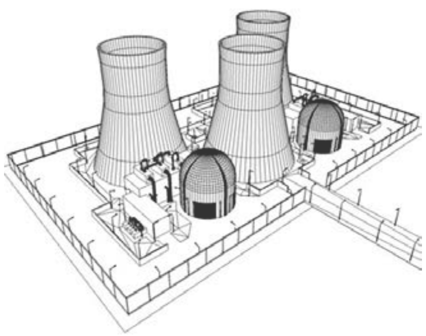
Short-term Electricity Markets

(Basic structure)

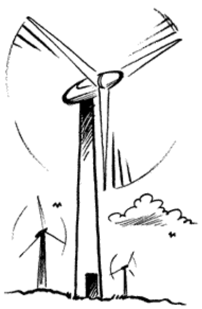


Short-term Electricity Markets
(Basic structure)

Day-ahead market



Balancing market

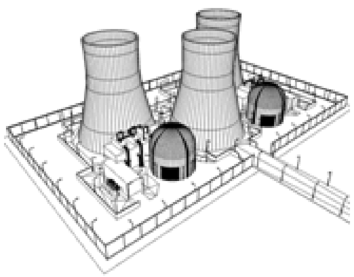


Inflexible units (need advance planning)

Wind producers/consumers (need balancing energy)

Dealing with Uncertain Supply

(The need for flexibility)



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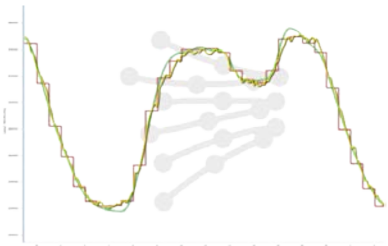

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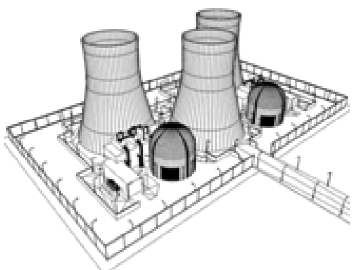
Day-ahead market

Balancing

Dealing with Uncertain Supply

(The need for flexibility)



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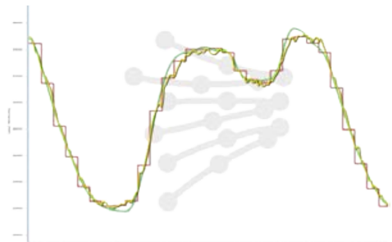

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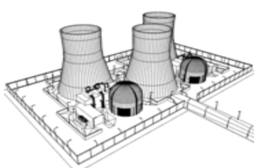
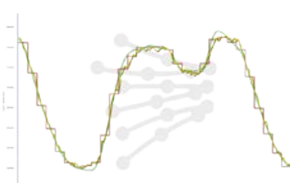
Day-ahead market

Balancing

Variability cost





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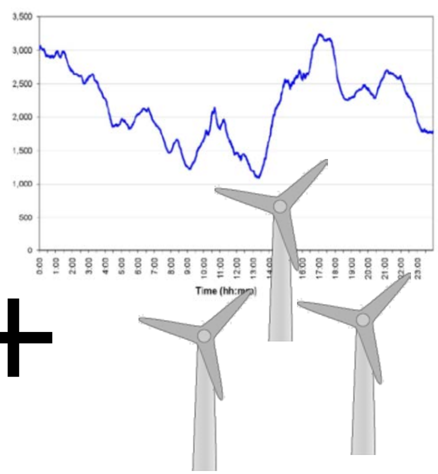

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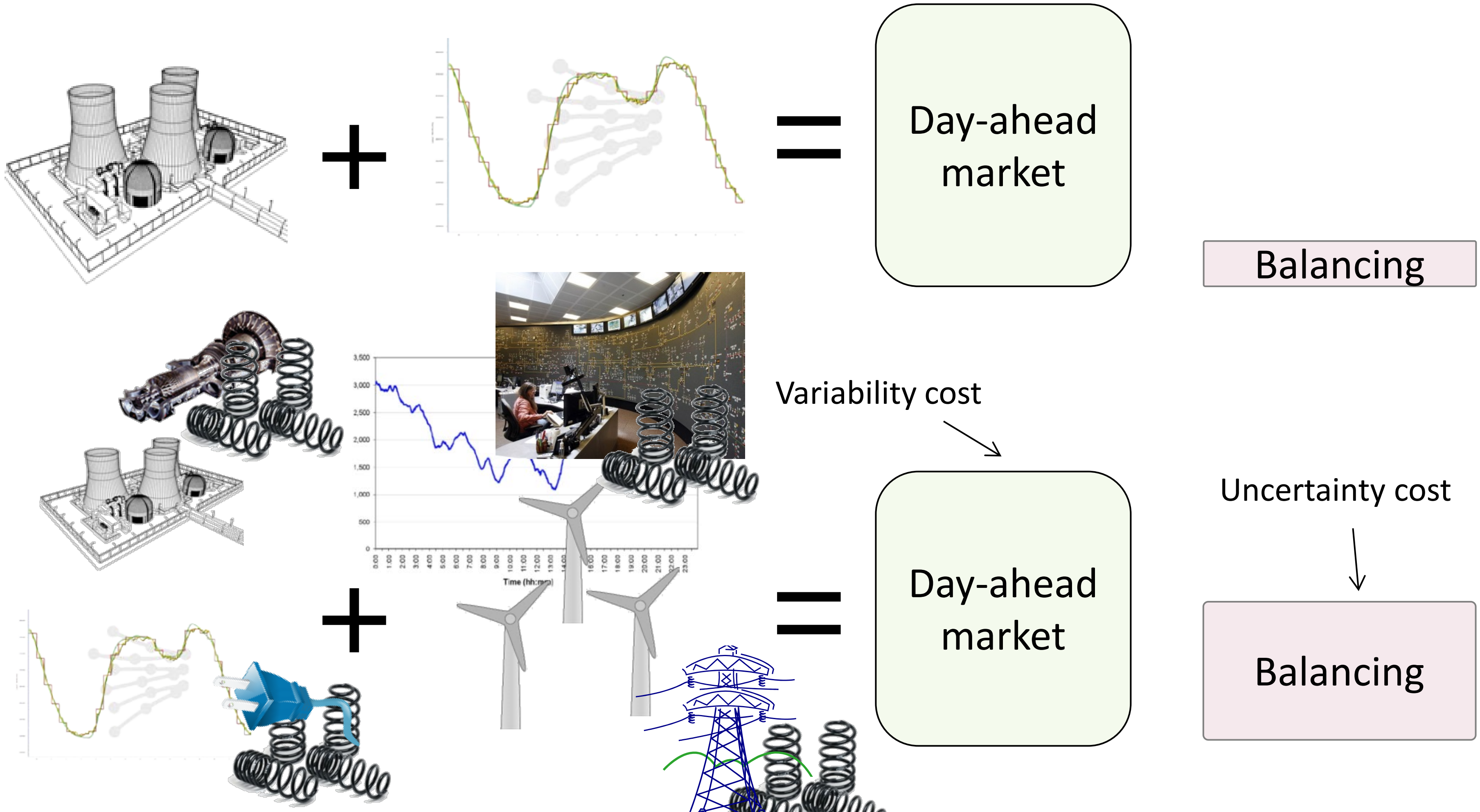
Day-ahead market

Uncertainty cost

Balancing

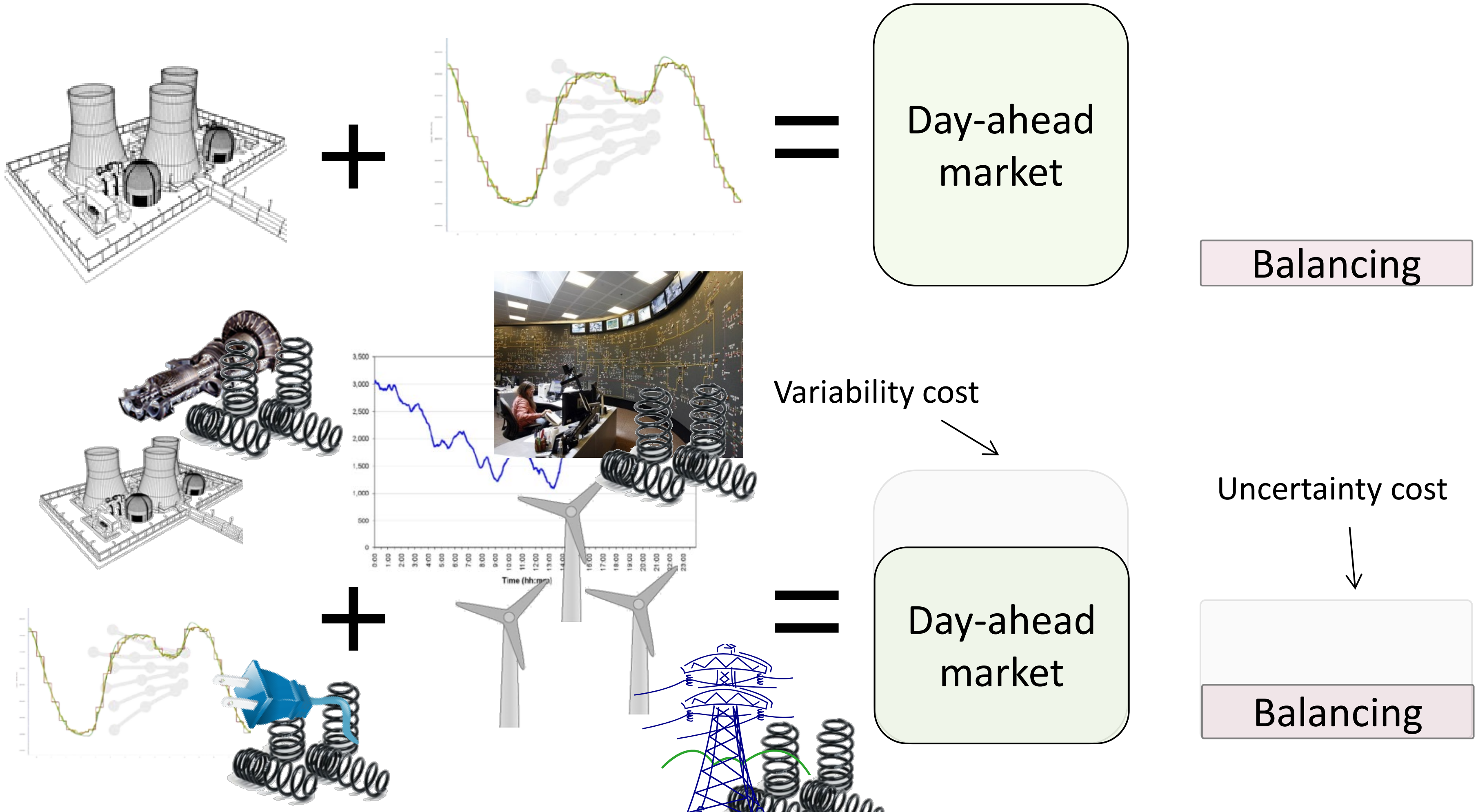
Dealing with Uncertain Supply

(The need for flexibility)



Dealing with Uncertain Supply

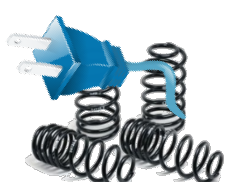
(The need for flexibility)

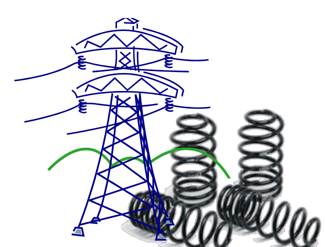


Dealing with Uncertain Supply

(The need for flexibility)

Flexibility is a must!

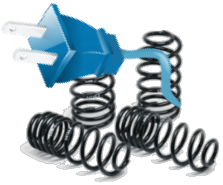


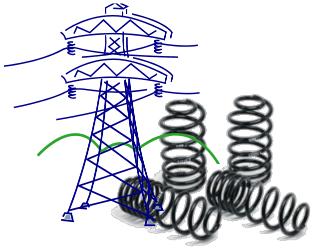


Dealing with Uncertain Supply

(The need for flexibility)

Flexibility is a must!

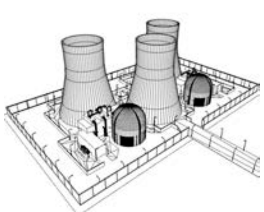




Dealing with Uncertain Supply
(Market mechanisms)

Day-ahead market

Balancing market



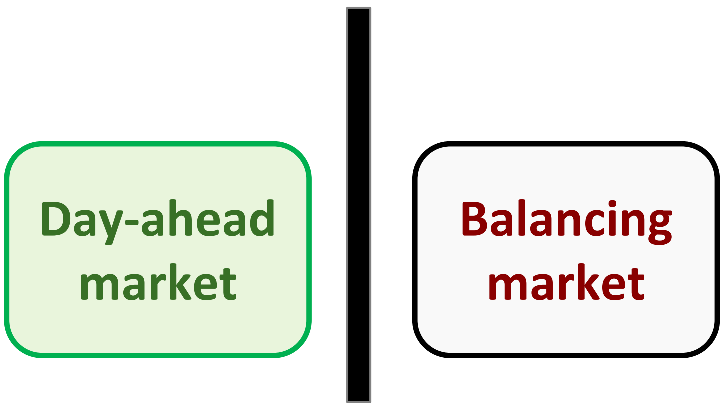
Time

Day d-1

Day d

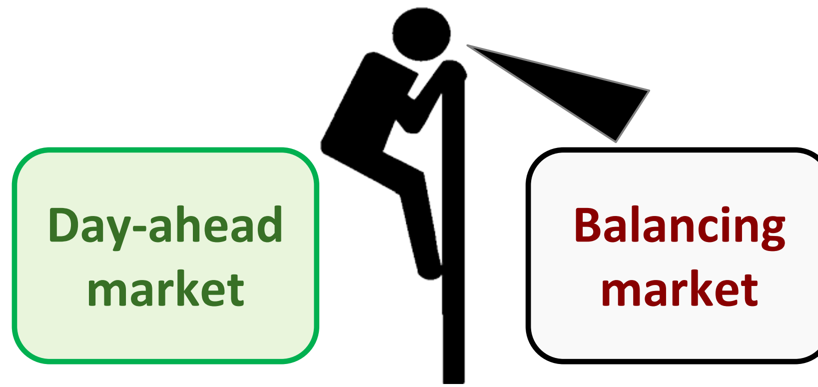
Dealing with Uncertain Supply
(Market mechanisms)

The design of the market conditions the value of system flexibility



Uncoordinated market (UM)

Inefficient management of system flexibility to cope with variability and uncertainty



Pre-emptive market (PM)

Perfect management of system flexibility to cope with variability and uncertainty

Dealing with Uncertain Supply

(Market mechanisms)

Uncoordinated market (UM)	Pre-emptive market (PM)
Day-ahead market	Day-ahead market Balancing prognosis
$\downarrow x^D$	$\downarrow x^D$
Balancing market	Balancing market

Uncoordinated market (UM)
(DAM and BM are cleared independently)

Pre-emptive market (PM)
(Day-ahead energy dispatch decisions account for balancing operation)

Dealing with Uncertain Supply

(Uncoordinated market)

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

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

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

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

Typically the (conditional) expected production!

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

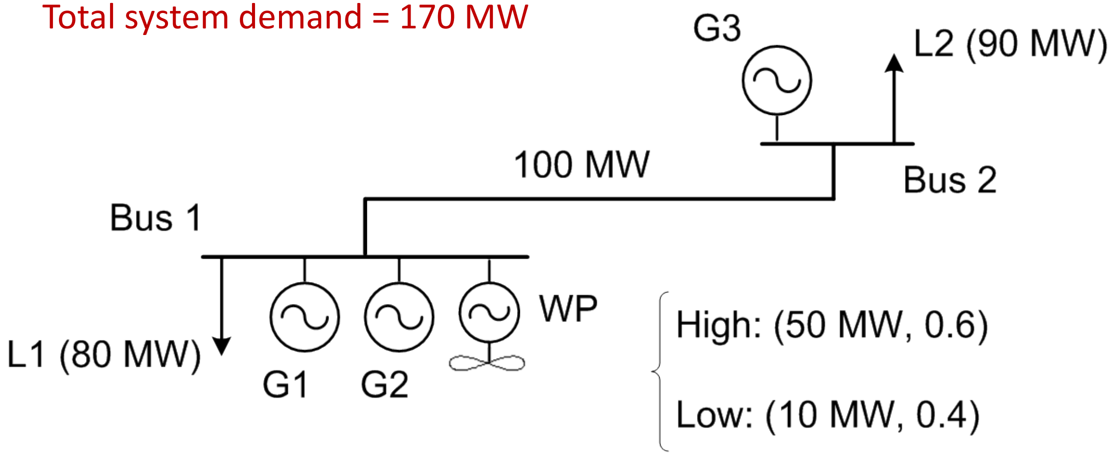
$$\underset{y_{\omega'}}{Minimize} \quad C^B(y_{\omega'})$$

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

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

Dealing with Uncertain Supply (Example)

Total system demand = 170 MW



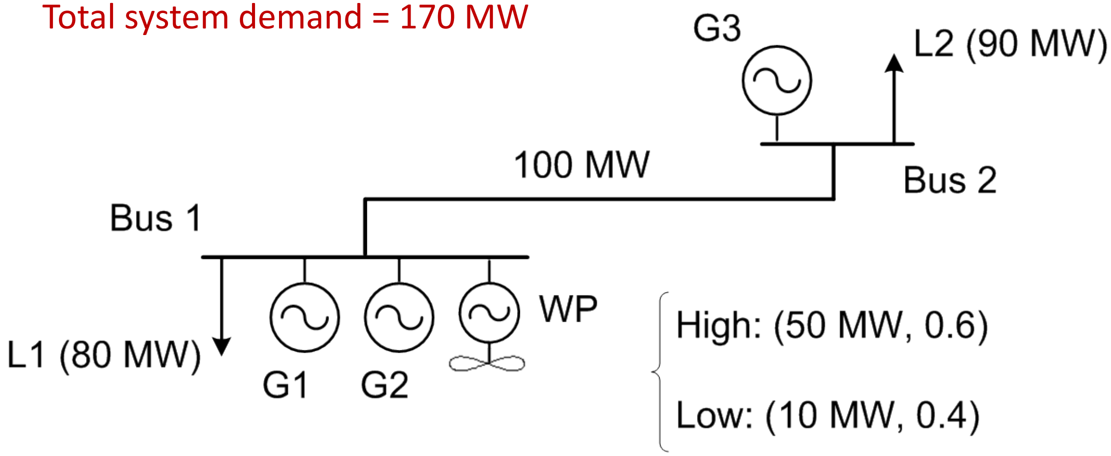
- Unit capacity and offer cost in DAM

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

Powers in MW; costs in \$/MWh

Dealing with Uncertain Supply (Example)

Total system demand = 170 MW



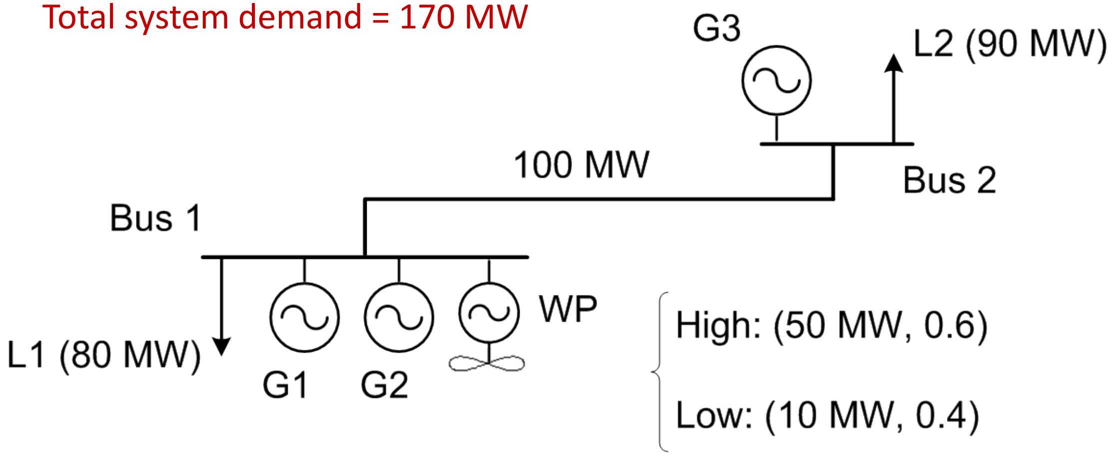
- Unit capacity and offer cost in DAM
- Offer limit and cost for the energy sold in BM

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

Powers in MW; costs in \$/MWh

Dealing with Uncertain Supply (Example)

Total system demand = 170 MW



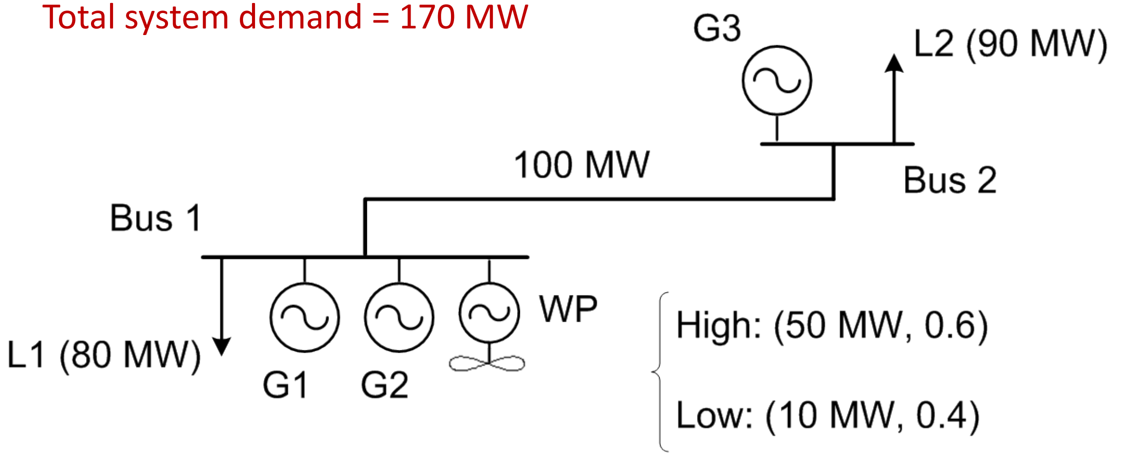
- Unit capacity and offer cost in DAM
- Offer limit and cost for the energy sold in BM
- Offer limit and cost for the energy repurchased in BM

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

Powers in MW; costs in $/MWh

Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW



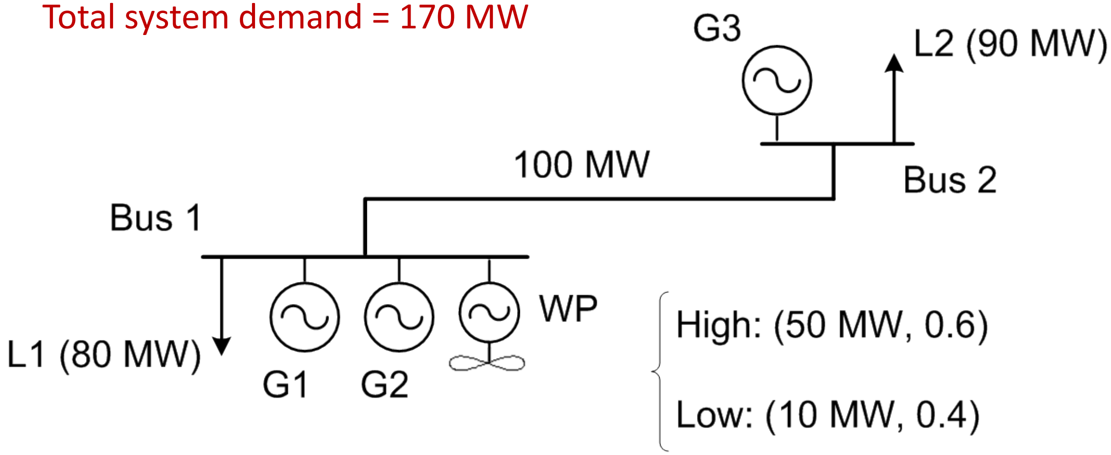
Expensive, but flexible

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

Powers in MW; costs in $/MWh

Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW



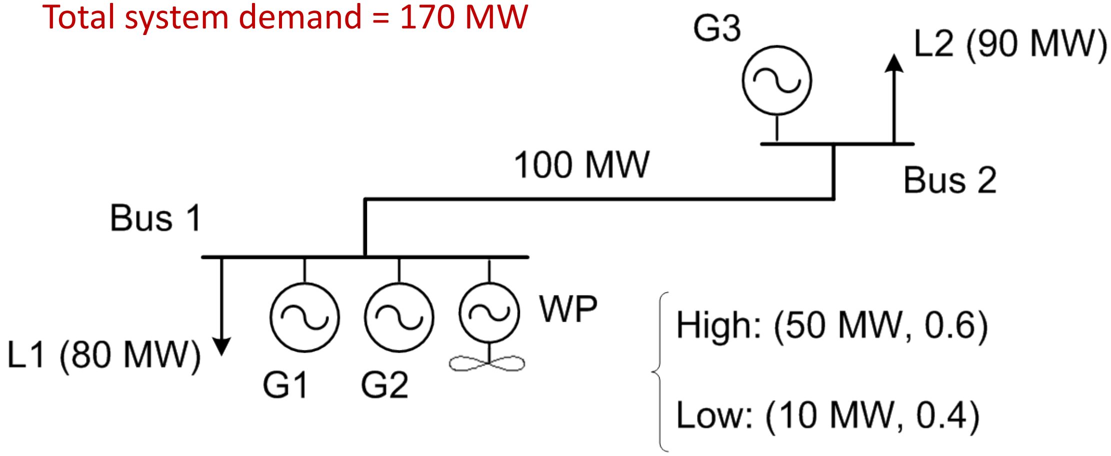
Less expensive, but inflexible

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

Powers in MW; costs in $/MWh

Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW



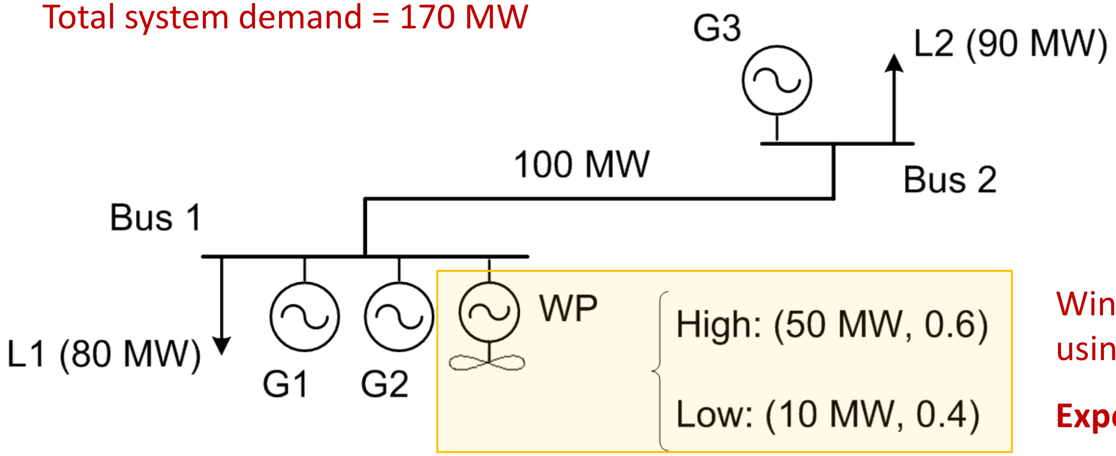
Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Cheap, but inflexible

Powers in MW; costs in $/MWh

Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW



Wind power production modeled using two scenarios

Expected production = 34 MW

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

Powers in MW; costs in $/MWh

Dealing with Uncertain Supply

(Uncoordinated market)

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

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

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

$$\text{Min.} \;\; 35p_{G_1} + 30p_{G_2} + 10p_{G_3}$$
$$\text{s.t.} \;\; p_{G_1} + p_{G_2} + p_W - 80 = -\frac{\delta_2^0}{0.13} \, ,$$
$$p_{G_3} - 90 = \frac{\delta_2^0}{0.13} \, ,$$
$$p_{G_1} \leq 100 \, , \quad p_{G_2} \leq 110 \, , \quad p_{G_3} \leq 50 \, ,$$
$$-100 \leq \frac{\delta_2^0}{0.13} \leq 100 \, ,$$
$$p_W \leq 34 \, ,$$
$$p_{G_1} \, , \; p_{G_2} \, , \; p_{G_3} \, , \; p_W \geq 0 \, ,$$

Dealing with Uncertain Supply

(Pre-emptive market)

$$\begin{aligned} &\underset{p_G, p_W, \delta^0}{\text{Minimize}} \quad C^D(p_G, p_W) \\ &\text{s.t.} \quad h^D(p_G, p_W, \delta^0) - l = 0 \\ &\qquad g^D(p_G, \delta^0) \le 0 \\ &\qquad p_W \le \hat{W} \end{aligned}$$

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

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

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

Balancing prognosis

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

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

Dealing with Uncertain Supply
(Pre-emptive market)

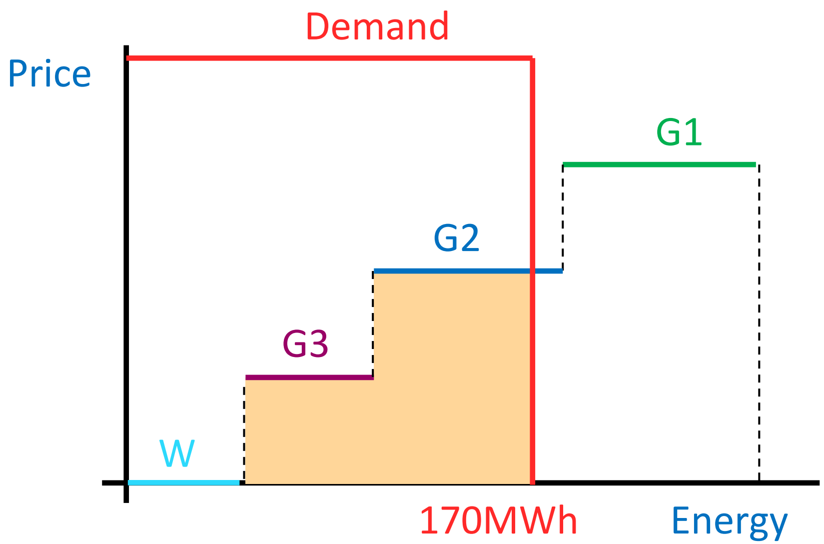
- Two-stage stochastic programming problem
- Expectation of the balancing costs: It requires probabilistic forecasts
- Scenario-based modeling of uncertainty
- Good modeling $\Rightarrow$ many scenarios $\Rightarrow$ increased dimensionality

$$\text{Min. } 35p_{G_1} + 30p_{G_2} + 10p_{G_3} + 0.6\Big(40r^+_{G_1h} - 34r^-_{G_1h} + 200\left(l^{\text{shed}}_{1h} + l^{\text{shed}}_{2h}\right)\Big) + 0.4\Big(40r^+_{G_1l} - 34r^-_{G_1l} + 200\left(l^{\text{shed}}_{1l} + l^{\text{shed}}_{2l}\right)\Big)$$

s.t. Day-ahead dispatch equations +

$$p_W \leq 50\,,$$
$$r^+_{G_1h} - r^-_{G_1h} + l^{\text{shed}}_{1h} + 50 - p_W - W^{\text{spill}}_h = \frac{(\delta^0_2 - \delta_{2h})}{0.13}\,,$$
$$r^+_{G_1l} - r^-_{G_1l} + l^{\text{shed}}_{1l} + 10 - p_W - W^{\text{spill}}_l = \frac{(\delta^0_2 - \delta_{2l})}{0.13}\,,$$
$$l^{\text{shed}}_{2h} = -\frac{(\delta^0_2 - \delta_{2h})}{0.13}\,,$$
$$l^{\text{shed}}_{2l} = -\frac{(\delta^0_2 - \delta_{2l})}{0.13}\,,$$
$$p_{G_1} + r^+_{G_1h} \leq 100\,,\quad p_{G_1} + r^+_{G_1l} \leq 100\,,$$
$$p_{G_1} - r^-_{G_1h} \geq 0\,,\quad p_{G_1} - r^-_{G_1l} \geq 0\,,$$
$$-100 \leq \frac{\delta_{2h}}{0.13} \leq 100\,,\quad -100 \leq \frac{\delta_{2l}}{0.13} \leq 100\,,$$
$$r^+_{G_1h} \leq 20\,,\quad r^+_{G_1l} \leq 20\,,$$
$$r^-_{G_1h} \leq 40\,,\quad r^-_{G_1l} \leq 40\,,$$
$$W^{\text{spill}}_h \leq 50\,,\quad W^{\text{spill}}_l \leq 10\,,$$
$$l^{\text{shed}}_{1h} \leq 80\,,\quad l^{\text{shed}}_{1l} \leq 80\,,\quad l^{\text{shed}}_{2h} \leq 90\,,\quad l^{\text{shed}}_{2l} \leq 90\,,$$
$$r^+_{G_1h}\,, r^+_{G_1l}\,, r^-_{G_1h}\,, r^-_{G_1l}\,, W^{\text{spill}}_h, W^{\text{spill}}_l, l^{\text{shed}}_{1h}\,, l^{\text{shed}}_{1l}\,, l^{\text{shed}}_{2h}\,, l^{\text{shed}}_{2l} \geq 0\,,$$

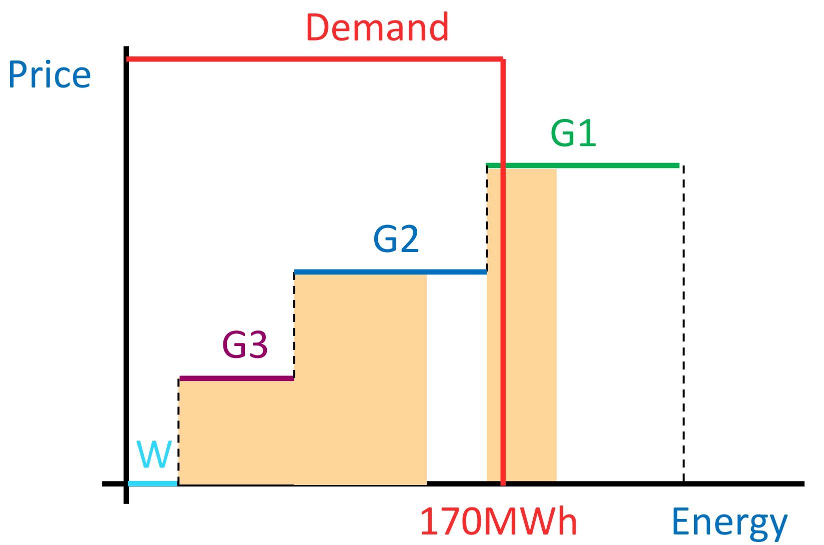
Example



Uncoordinated market (UM)

Unit	P^{max}	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh



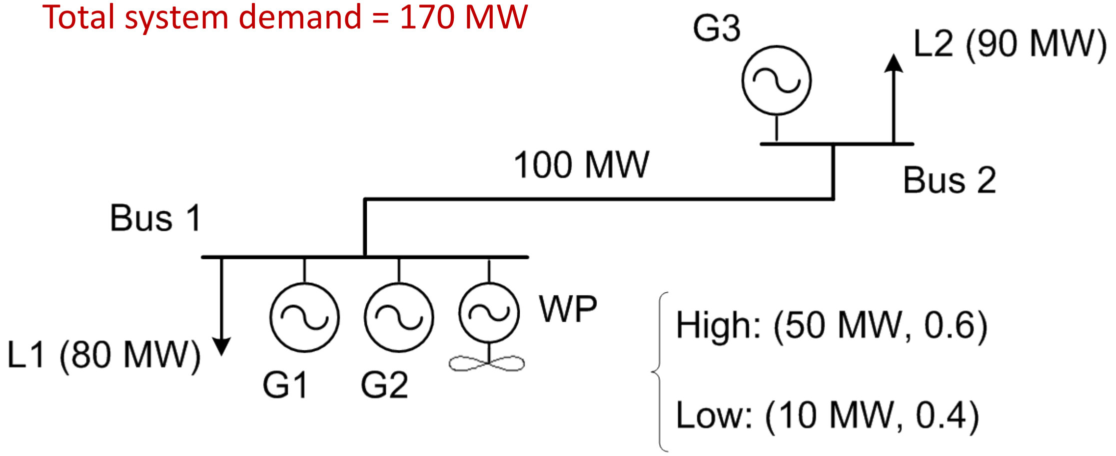
Pre-emptive market (PM)

Unit	P^{max}	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

Powers in MW; costs in $/MWh

Example

Total system demand = 170 MW



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Unit	P^{max}	C	P^{sch}
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Powers in MW; costs in $/MWh

Pre-emptive market (PM)

Unit	P^{max}	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

Powers in MW; costs in $/MWh

- The wind producer is dispatched only to 10 MW
- G1 is dispatched to 40, even though it is more expensive than G2
- The “traditional” cost merit-order principle does not hold in PM
- G1 is dispatched to exploit its ability to reduce production in real time

Example

$$\underset{r_{1h}^{+},r_{1h}^{-},L_{jh}^{\text{sh}},W_{h}^{\text{sp}},\delta_{2h}}{\text{Min.}} \quad 40r_{1h}^{+} - 34r_{1h}^{-} + 200\left(L_{1h}^{\text{sh}} + L_{2h}^{\text{sh}}\right)$$

$$\text{s.t.} \quad r_{1h}^{+} - r_{1h}^{-} + L_{1h}^{\text{sh}} + 50 - p_{W}^{*} - W_{h}^{\text{sp}} = -\left(\delta_{2h} - \delta_{2}^{0*}\right)/0.13,$$

$$L_{2h}^{\text{sh}} = \left(\delta_{2h} - \delta_{2}^{0*}\right)/0.13,$$

$$r_{1h}^{+} \leq 20, \quad r_{1h}^{-} \leq 40,$$

$$r_{1h}^{+} \leq 100 - p_{G_1}^{*}, \quad r_{1h}^{-} \leq p_{G_1}^{*},$$

$$L_{1h}^{\text{sh}} \leq 80; \quad L_{2h}^{\text{sh}} \leq 90,$$

$$W_{h}^{\text{sp}} \leq 50,$$

$$-100 \leq \frac{\delta_{2h}}{0.13} \leq 100,$$

$$r_{1h}^{+},\ r_{1h}^{-},\ L_{1h}^{\text{sh}},\ L_{2h}^{\text{sh}},\ W_{h}^{\text{sp}} \geq 0,$$

Scenario “high”

Scenario “low”

$$\underset{r_{1l}^{+},r_{1l}^{-},L_{jl}^{\text{sh}},W_{l}^{\text{sp}},\delta_{2l}}{\text{Min.}} \quad 40r_{1l}^{+} - 34r_{1l}^{-} + 200\left(L_{1l}^{\text{sh}} + L_{2l}^{\text{sh}}\right)$$

$$\text{s.t.} \quad r_{1l}^{+} - r_{1l}^{-} + L_{1l}^{\text{sh}} + 10 - p_{W}^{*} - W_{l}^{\text{sp}} = -\left(\delta_{2l} - \delta_{2}^{0*}\right)/0.13,$$

$$L_{2l}^{\text{sh}} = \left(\delta_{2l} - \delta_{2}^{0*}\right)/0.13,$$

$$r_{1l}^{+} \leq 20, \quad r_{1l}^{-} \leq 40,$$

$$r_{1l}^{+} \leq 100 - p_{G_1}^{*}, \quad r_{1l}^{-} \leq p_{G_1}^{*},$$

$$L_{1l}^{\text{sh}} \leq 80; \quad L_{2l}^{\text{sh}} \leq 90,$$

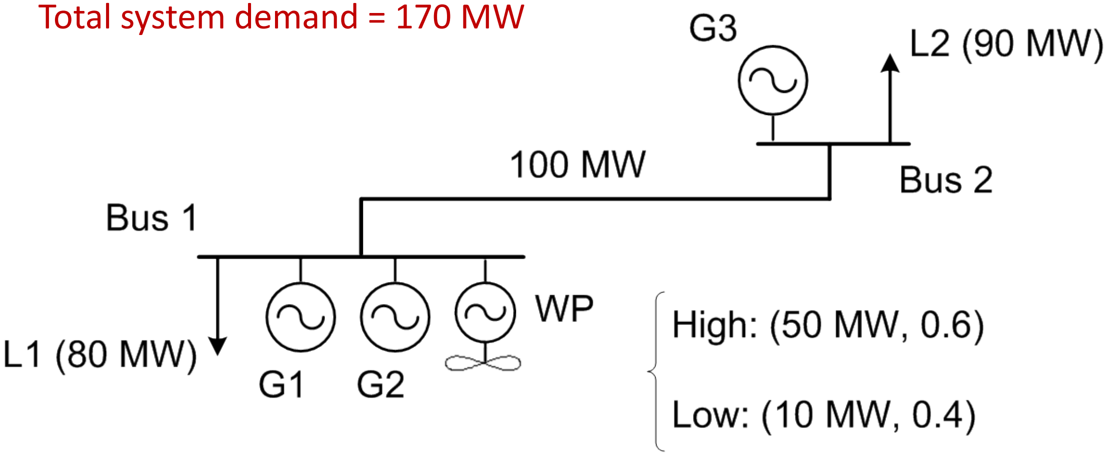
$$W_{l}^{\text{sp}} \leq 10,$$

$$-100 \leq \frac{\delta_{2l}}{0.13} \leq 100,$$

$$r_{1l}^{+},\ r_{1l}^{-},\ L_{1l}^{\text{sh}},\ L_{2l}^{\text{sh}},\ W_{l}^{\text{sp}} \geq 0,$$

Example

Total system demand = 170 MW



Uncoordinated market (UM)

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

Powers in MW; costs in \$/MWh

	Total	Day ahead	Balancing	Load shedding
UM	3720	3080	320	320
PM	3184	4000	-816	0

Costly!
(€200/MWh)

Pre-emptive market (PM)

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

Powers in MW; costs in \$/MWh

PM results in a more expensive day-ahead dispatch that leads, however, to a much more efficient balancing operation

Dealing with Uncertain Supply

(Pre-emptive market)

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

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

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

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

Expectation

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

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

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

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

Worst-case scenario

Balancing prognosis

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

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

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

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

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

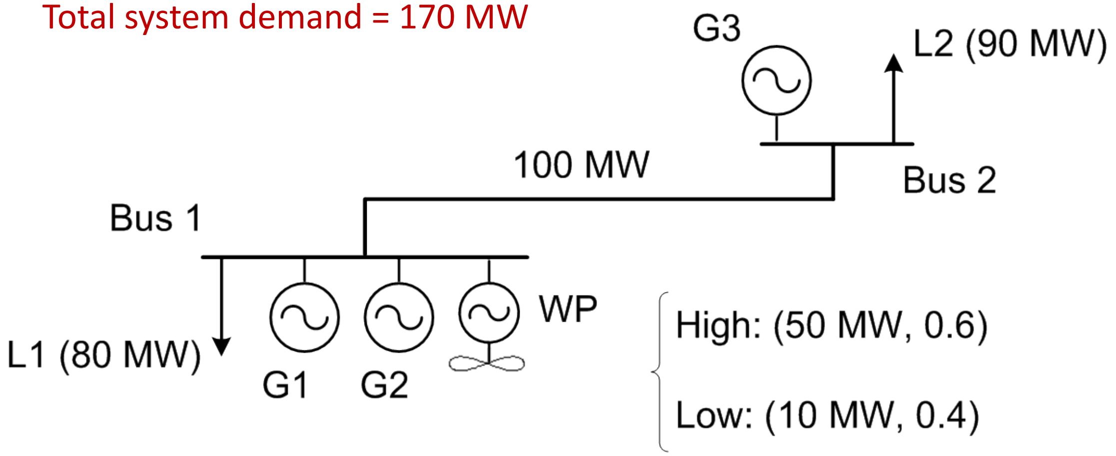
$$\underset{y_{\omega'}}{Minimize} \quad C^B(y_{\omega'})$$

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

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

Example

Total system demand = 170 MW



Uncoordinated market (UM)

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

Powers in MW; costs in $/MWh

Robust PM

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

Powers in MW; costs in $/MWh

Stochastic PM

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

Powers in MW; costs in $/MWh

Example

On average

	Total	Day ahead	Balancing	Load shedding
UM	3720	3080	320	320
SPM	3184	4000	-816	0
RPM	3800	3800	0	0

Scheduled production (MWh)

Unit	**UM**	**SPM**	**RPM**
G1	0	40	0
G2	86	70	110
G3	50	50	50
WP	34	10	10

In scenario low (worst-case)

	Total	Day ahead	Balancing	Load shedding
UM	4680	3080	800	800
SPM	4000	4000	0	0
RPM	3800	3800	0	0

In scenario high (best-case)

	Total	Day ahead	Balancing	Load shedding
UM	3080	3080	0	0
SPM	2640	4000	-1360	0
RPM	3800	3800	0	0

Prices & Revenues

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

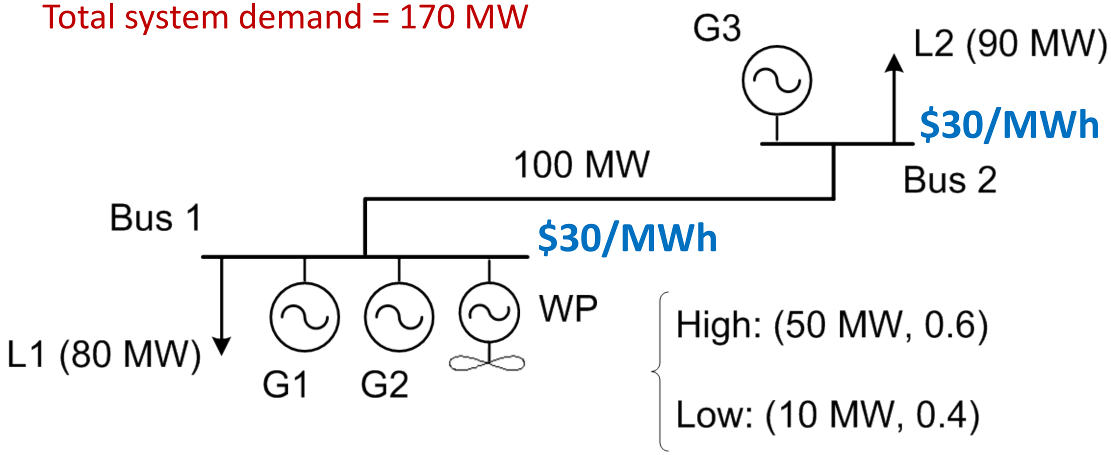
$$\downarrow \; p_G^*, p_W^*, \delta^{0*}$$

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

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

Example

Total system demand = 170 MW



Uncoordinated market (UM)

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Powers in MW; costs in $/MWh

Stochastic PM

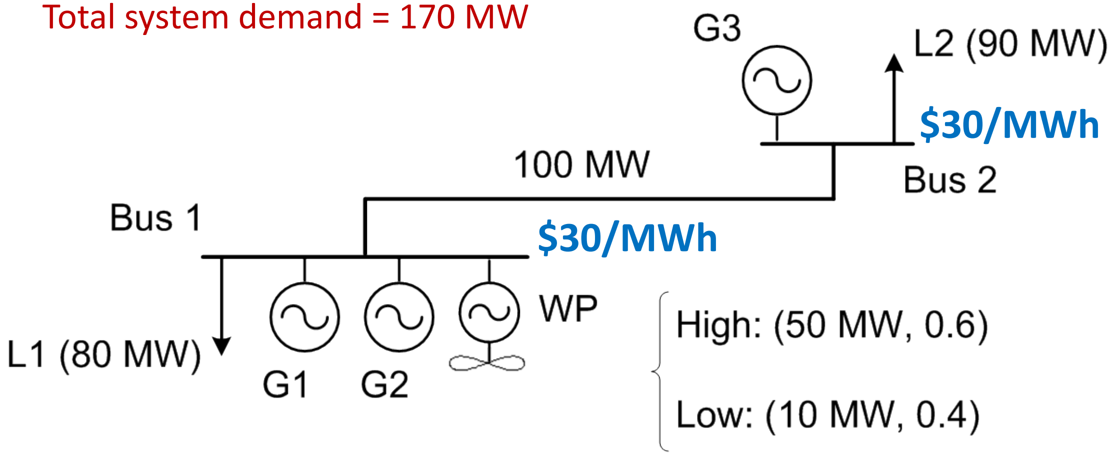
Unit	P^{max}	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

Powers in MW; costs in $/MWh

In "Stochastic PM" unit G1 is dispatched day ahead in a **loss-making position**

Example

Total system demand = 170 MW



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G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Profit G1	Expected	Per scenario	
		High	Low
UM	1320	0	3300
Stoch PM	24	173.33	-200

In “Stochastic PM” unit G1 incur losses if scenario “low” happens

Stochastic PM

Unit	P^{max}	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

Powers in MW; costs in $/MWh

Dealing with Uncertain Supply
(Alternatives)

- ✓ The stochastic dispatch is more efficient, but …
  - may schedule flexible units in a loss-making position;
  - guarantees cost recovery for flexible producers **only in expectation**, not per scenario;
  - this expectation depends on a centralized forecasting tool out of producers' control.
- ✓ Is there a way to approximate "Stochastic PM" as much as possible while resolving the issues above?

Dealing with Uncertain Supply

(Centralized dispatch of stochastic production)

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

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

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

$$p_W \le \hat{W}$$

Do we have something better than the expected production?

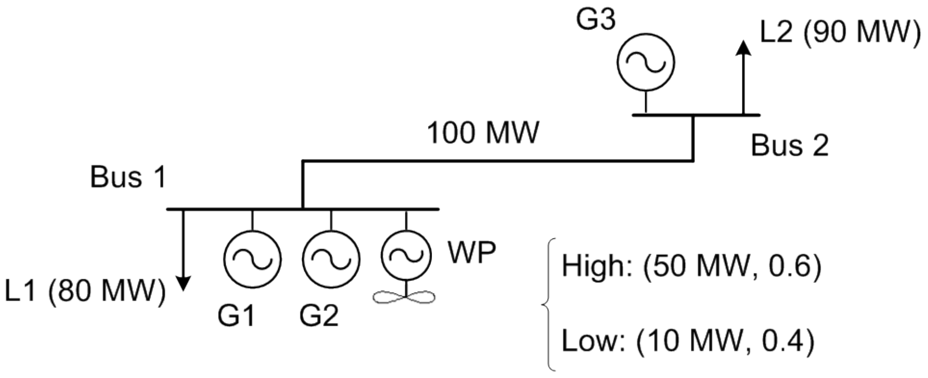
$$p_G^*, p_W^*, \delta^{0*}$$

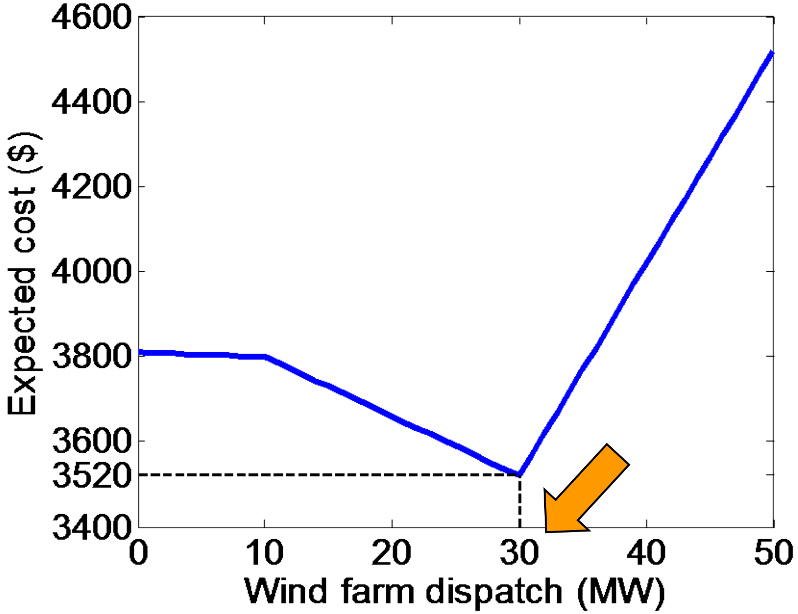
$$\underset{y_{\omega'}}{\text{Minimize}} \quad C^B(y_{\omega'})$$

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

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

Example
(Centralized dispatch of Stoch. Prod.)





Uncoordinated market (UM)

Unit	P^{max}	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

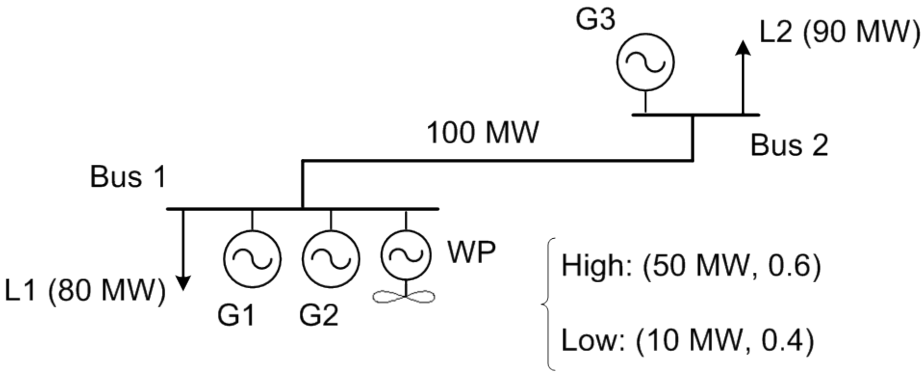
Improved UM (IUM)

Unit	P^{max}	C	P^{sch}
G1	100	35	0
G2	110	30	90
G3	50	10	50
WP	34	0	30

Powers in MW; costs in $/MWh

Example

(Centralized dispatch of Stoch. Prod.)



Uncoordinated market (UM)

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

Powers in MW; costs in $/MWh

	Total	Day ahead	Balancing	Load shedding
UM	3720	3080	320	320
Stoch PM	3184	4000	-816	0
IUM	3520	3200	320	0

Improved

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	90
G3	50	10	50
WP	34	0	30

Powers in MW; costs in $/MWh

Dealing with Uncertain Supply

(Centralized dispatch of stochastic production)

- ✓ How do we compute the "best" schedule for the stochastic power production?

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

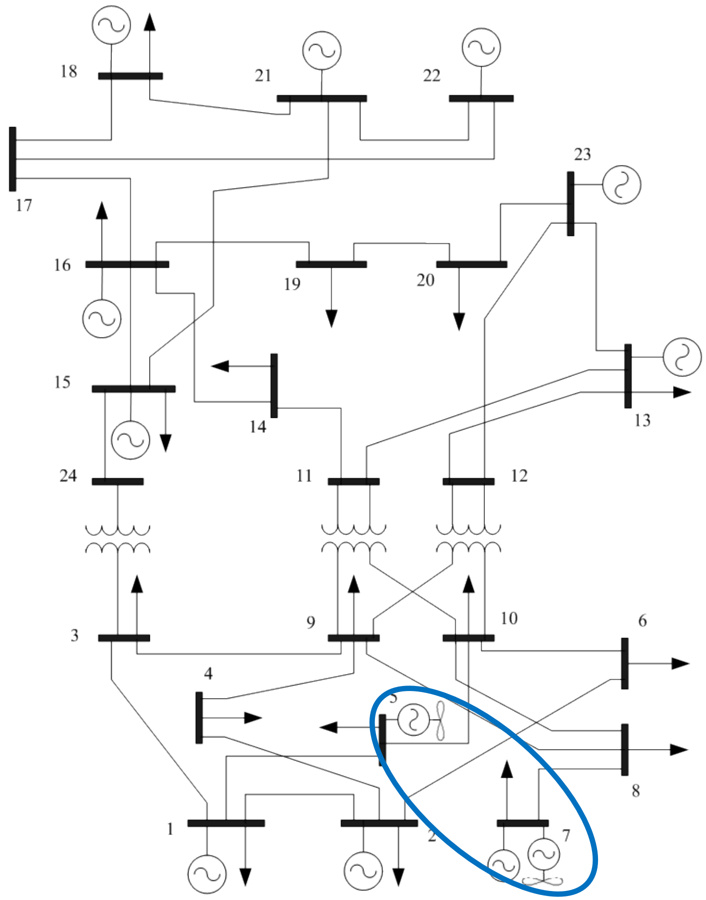
Dealing with Uncertain Supply

Centralized dispatch of stochastic production

$$
\begin{aligned}
\text{Min. } & 35p_{G_1} + 30p_{G_2} + 10p_{G_3} + 0.6\left(40r^{+}_{G_1h} - 34r^{-}_{G_1h} + 200\left(l^{\text{shed}}_{1h} + l^{\text{shed}}_{2h}\right)\right) \\
& + 0.4\left(40r^{+}_{G_1l} - 34r^{-}_{G_1l} + 200\left(l^{\text{shed}}_{1l} + l^{\text{shed}}_{2l}\right)\right) \\
\text{s.t. } & r^{+}_{G_1h} - r^{-}_{G_1h} + l^{\text{shed}}_{1h} + 50 - p_W - W^{\text{spill}}_h = \frac{(\delta^0_2 - \delta_{2h})}{0.13}, \\
& r^{+}_{G_1l} - r^{-}_{G_1l} + l^{\text{shed}}_{1l} + 10 - p_W - W^{\text{spill}}_l = \frac{(\delta^0_2 - \delta_{2l})}{0.13}, \\
& l^{\text{shed}}_{2h} = -\frac{\left(\delta^0_2 - \delta_{2h}\right)}{0.13}, \\
& l^{\text{shed}}_{2l} = -\frac{\left(\delta^0_2 - \delta_{2l}\right)}{0.13}, \\
& p_{G_1} + r^{+}_{G_1h} \leqslant 100, \quad p_{G_1} + r^{+}_{G_1l} \leqslant 100, \\
& p_{G_1} - r^{-}_{G_1h} \geqslant 0, \quad p_{G_1} - r^{-}_{G_1l} \geqslant 0, \\
& -100 \leqslant \frac{\delta_{2h}}{0.13} \leqslant 100, \quad -100 \leqslant \frac{\delta_{2l}}{0.13} \leqslant 100, \\
& r^{+}_{G_1h} \leqslant 20, \quad r^{+}_{G_1l} \leqslant 20, \\
& r^{-}_{G_1h} \leqslant 40, \quad r^{-}_{G_1l} \leqslant 40, \\
& W^{\text{spill}}_h \leqslant 50, \; W^{\text{spill}}_l \leqslant 10, \\
& l^{\text{shed}}_{1h} \leqslant 80, \quad l^{\text{shed}}_{1l} \leqslant 80, \quad l^{\text{shed}}_{2h} \leqslant 90, \; l^{\text{shed}}_{2l} \leqslant 90, \\
& r^{+}_{G_1h}, \; r^{+}_{G_1l}, \; r^{-}_{G_1h}, r^{-}_{G_1l}, \; W^{\text{spill}}_h, \; W^{\text{spill}}_l, \; l^{\text{shed}}_{1h}, \; l^{\text{shed}}_{1l}, \; l^{\text{shed}}_{2h}, \; l^{\text{shed}}_{2l} \geqslant 0, \\
& 0 \leqslant p^{\max}_W \leqslant 50,
\end{aligned}
$$

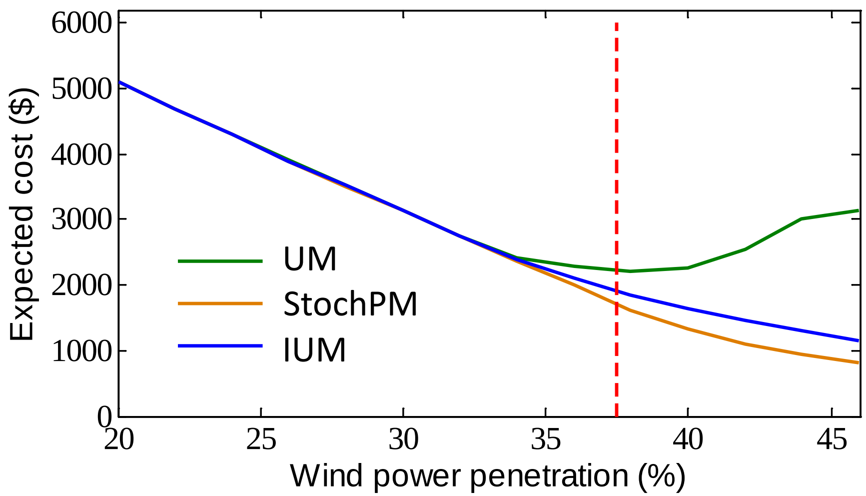
$$
\boxed{
\begin{aligned}
& \left(p_{G_1}, \; p_{G_2}, \; p_{G_3}, \; p_W, \; \delta^0_2\right) \in \arg \underset{x_{G_1}, \, x_{G_2}, \, x_{G_3}, \, x_W, \, \theta}{\text{Minimize}} \; 35x_{G_1} + 30x_{G_2} + 10x_{G_3} \\
& \quad \text{s.t. } x_{G_1} + x_{G_2} + x_W - 80 = -\frac{\theta}{0.13} : \lambda^{\text{D}}_1, \\
& \qquad x_{G_3} - 90 = \frac{\theta}{0.13} : \lambda^{\text{D}}_2, \\
& \qquad x_{G_1} \leqslant 100 : \bar{\mu}_{G_1}, \quad x_{G_2} \leqslant 110 : \bar{\mu}_{G_2}, \quad x_{G_3} \leqslant 50 : \bar{\mu}_{G_3}, \\
& \qquad -100 \leqslant \frac{\theta}{0.13} \leqslant 100 : (\underline{\mu}_\delta, \bar{\mu}_\delta), \\
& \qquad x_W \leqslant p^{\max}_W : \bar{\rho}, \\
& \qquad x_{G_1}, \; x_{G_2}, \; x_{G_3}, \; x_W \geqslant 0 : (\underline{\mu}_{G_1}, \; \underline{\mu}_{G_2}, \; \underline{\mu}_{G_3}, \; \underline{\rho}),
\end{aligned}
}
$$

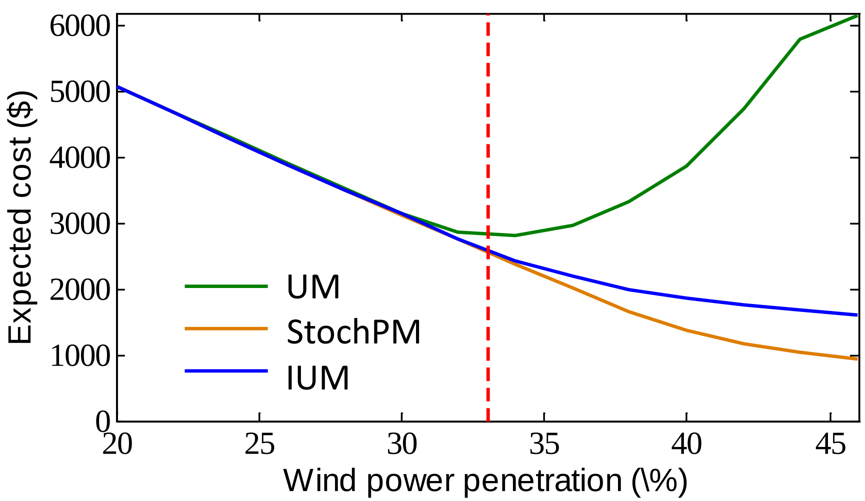
24-bus Case Study



- 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 "IUM" and "StochPM", higher penetrations of stochastic production never lead to an increase in the expected cost
- "IUM" and "StochPM" are robust to the spatial correlation of stochastic energy sources

24-bus Case Study

Wind penetration 38% ρ = 0.35		Unit			
		1	6	11	12
Stoch PM	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
UM	Expected profit ($)	379.8	359.7	724.9	389.1
IUM	Expected profit ($)	170.2	263.7	531.6	178.7

Dealing with Uncertain Supply

(The role of virtual bidding)

- ✓ Is there a way to sidestep the bilevel program in practice?
- ✓ Yes, in some cases, by allowing for virtual bidding. See:

Juan M. Morales and Salvador Pineda (2016). On the Inefficiency of the Merit Order in Forward Electricity Markets with Uncertain Supply. Available on arXiv:

http://arxiv.org/abs/1507.06092

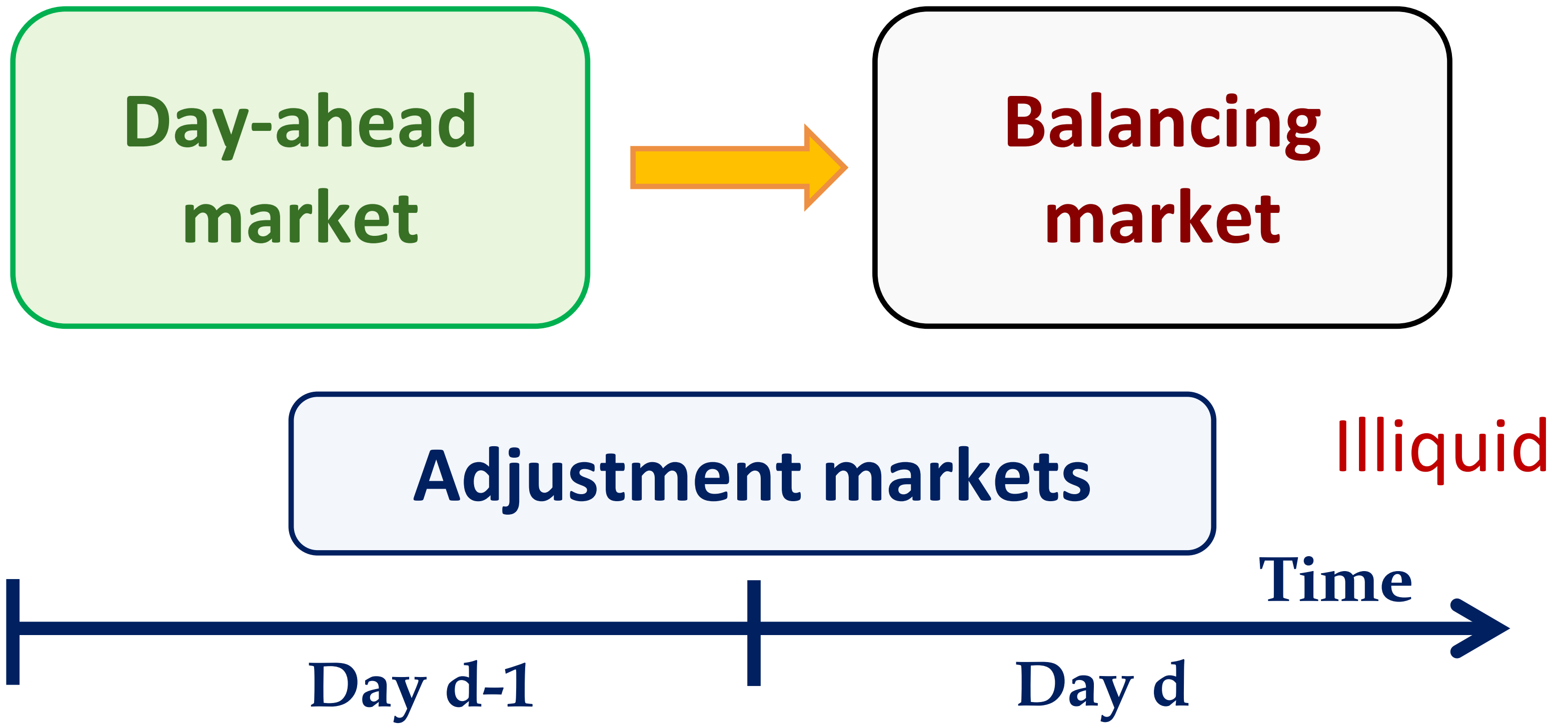
- ✓ Risk-neutral virtual bidder:

$$\underset{p_V, \Delta p_V}{\text{Maximize}} \quad p_V \lambda^D + \int_{\Omega} \Delta p_V \lambda^B(\omega) f(\omega) d\omega$$

$$\text{s.t.} \quad p_V + \Delta p_V = 0$$

Other Mechanisms

- Increase in the number of market stages: Adjustment markets allow redefining forward positions and trading with a lesser degree of uncertainty



Other Mechanisms

- Guarantee balancing resources
- Help flexible producers (missing money in price-capped energy markets)
- Demand curve? Cost allocation?

Day-ahead market

Reserve/flexiramp markets

Balancing market

Day d

Day d-1

Time

Concluding Remarks

- The growing penetration of weather-driven energy sources calls not only for increased system flexibility, but also for a better utilization of the existing one.

- Power systems are to be operated, therefore, with a higher degree of flexibility: market mechanisms that anticipate the need for flexibility and plan accordingly are promising solutions.

- Critical market modifications/additions with the potential to increase system efficiency and reliability, while being easily implementable are to be identified.

- Wrong current market practices should also be pointed out: for example, forward markets should not clear the expected stochastic production by default.

- Remember that we are talking about markets: economic incentives and prices are to support the most efficient solution for the system.

Thanks for your attention!

Questions?