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

Juan M. Morales
Kgs. Lyngby, Denmark
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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
Inflexible units
(need advance planning)

Balancing market
Wind producers/consumers
(need balancing energy)
Dealing with Uncertain Supply
(The need for flexibility)

Day-ahead market

Balancing
Dealing with Uncertain Supply (The need for flexibility)

Day-ahead market + Variability cost = Balancing

Day-ahead market + Uncertainty cost = Balancing
Dealing with Uncertain Supply
(The need for flexibility)
Dealing with Uncertain Supply
(The need for flexibility)

Day-ahead market

Balancing

Variability cost

Uncertainty cost

Day-ahead market

Balancing
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)
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)

Day-ahead market

\[ x^D \]

Balancing market

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

Day-ahead market

Balancing prognosis

Balancing market

Pre-emptive market (PM)
(Day-ahead energy dispatch decisions account for balancing operation)
Dealing with Uncertain Supply
(Uncoordinated market)

\[
\begin{align*}
\text{Minimize} & \quad C^D(p_G, p_W) \\
\text{s.t.} & \quad h^D(p_G, p_W, \delta^0) - l = 0 \\
& \quad g^D(p_G, \delta^0) \leq 0 \\
& \quad p_W \leq \hat{W} \\
\end{align*}
\]

Typically the (conditional) expected production!

\[
\begin{align*}
\text{Minimize} & \quad C^B(y_{\omega'}) \\
\text{s.t.} & \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p^*_W = 0 \\
& \quad g^B(y_{\omega'}, \delta_{\omega'}, p^*_G; W_{\omega'}) \leq 0 \\
\end{align*}
\]
Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW

Unit capacity and offer cost in DAM

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

Powers in MW; costs in $/MWh

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<tr>
<th>Unit</th>
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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

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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

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Powers in MW; costs in $/MWh
Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW

Expensive, but flexible

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Powers in MW; costs in $/MWh
Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW

Less expensive, but inflexible

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Powers in MW; costs in $/MWh
Dealing with Uncertain Supply
(Example)

Total system demand = 170 MW

G1  100  35  40  34  20  40
G2  110  30
G3  50  10

Powers in MW; costs in $/MWh

Cheap, but inflexible
Dealing with Uncertain Supply (Example)

Total system demand = 170 MW

Wind power production modeled using two scenarios

Expected production = 34 MW

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Powers in MW; costs in $/MWh
Dealing with Uncertain Supply
(Uncoordinated market)

Minimize \( C^D(p_G, p_W) \)

\[ \begin{align*}
\text{s.t.} & \quad h^D(p_G, p_W, \delta^0) - l = 0 \\
& \quad g^D(p_G, \delta^0) \leq 0 \\
& \quad p_W \leq \hat{W}
\end{align*} \]

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

\[ \begin{align*}
\text{s.t.} & \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p^*_W = 0 \\
& \quad g^B(y_{\omega'}, \delta_{\omega'}, p^*_G; W_{\omega'}) \leq 0
\end{align*} \]

Min. \( 35p_{G1} + 30p_{G2} + 10p_{G3} \)

\[ \begin{align*}
\text{s.t.} & \quad p_{G1} + p_{G2} + p_W - 80 = -\frac{\delta^0}{0.13}, \\
& \quad p_{G3} - 90 = \frac{\delta^0}{0.13}, \\
& \quad p_{G1} \leq 100, \quad p_{G2} \leq 110, \quad p_{G3} \leq 50, \\
& \quad -100 \leq \frac{\delta^0}{0.13} \leq 100, \\
& \quad p_W \leq 34, \\
& \quad p_{G1}, \ p_{G2}, \ p_{G3}, \ p_W \geq 0,
\end{align*} \]
Dealing with Uncertain Supply
(Pre-emptive market)

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

\[ p^*_G, p^*_W, \delta^{0*} \]

\[ \text{Minimize} \quad C^B(y_{\omega'}) \]
\[ \text{s.t.} \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p^*_W = 0 \]
\[ g^B(y_{\omega'}, \delta_{\omega'}, p^*_G; W_{\omega'}) \leq 0 \]

\[ p^*_G, p^*_W, \delta^{0*} \]

\[ \text{Minimize} \quad C^D(p_G, p_W) + E_\omega \left[ C^B(y_{\omega'}) \right] \]
\[ \text{s.t.} \quad h^D(p_G, p_W, \delta^0) - l = 0 \]
\[ g^D(p_G, \delta^0) \leq 0 \]
\[ p_W \leq \bar{W} \]
\[ h^B(y_{\omega'}, \delta_{\omega'}, \delta^0) + W_{\omega'} - p_W = 0, \quad \forall \omega \]
\[ g^B(y_{\omega'}, \delta_{\omega'}, p_G; W_{\omega'}) \leq 0, \quad \forall \omega \]

Balancing prognosis
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

\[
\begin{align*}
\text{Min.} \quad & 35p_{G1} + 30p_{G2} + 10p_{G3} + 0.6 \left(40r_{G1h}^+ - 34r_{G1h}^- + 200 \left(\ell_{1h}^{\text{shed}} + \ell_{2h}^{\text{shed}}\right)\right) \\
& + 0.4 \left(40r_{G1l}^+ - 34r_{G1l}^- + 200 \left(\ell_{1l}^{\text{shed}} + \ell_{2l}^{\text{shed}}\right)\right)
\end{align*}
\]

\[
\begin{align*}
s.t. \quad & \text{Day-ahead dispatch equations} + \\
& p_W \leq 50, \\
& r_{G1h}^+ - r_{G1h}^- + \ell_{1h}^{\text{shed}} + 50 - p_W - W_h^{\text{spill}} = \frac{(\delta_0^0 - \delta_{2h})}{0.13}, \\
& r_{G1l}^+ - r_{G1l}^- + \ell_{1l}^{\text{shed}} + 10 - p_W - W_l^{\text{spill}} = \frac{(\delta_0^0 - \delta_{2l})}{0.13}, \\
& \ell_{2h}^{\text{shed}} = \frac{(\delta_0^0 - \delta_{2h})}{0.13}, \\
& \ell_{2l}^{\text{shed}} = \frac{(\delta_0^0 - \delta_{2l})}{0.13}, \\
& p_{G1} + r_{G1h}^+ \leq 100, \quad p_{G1} + r_{G1l}^+ \leq 100, \\
& p_{G1} - r_{G1h}^- \geq 0, \quad p_{G1} - r_{G1l}^- \geq 0, \\
& -100 \leq \frac{\delta_{2h}}{0.13} \leq 100, \quad -100 \leq \frac{\delta_{2l}}{0.13} \leq 100, \\
& r_{G1h}^+ \leq 20, \quad r_{G1l}^+ \leq 20, \\
& r_{G1h}^- \leq 40, \quad r_{G1l}^- \leq 40, \\
& W_h^{\text{spill}} \leq 50, \quad W_l^{\text{spill}} \leq 10, \\
& \ell_{1h}^{\text{shed}} \leq 80, \quad \ell_{1l}^{\text{shed}} \leq 80, \quad \ell_{2h}^{\text{shed}} \leq 90, \quad \ell_{2l}^{\text{shed}} \leq 90, \\
& r_{G1h}^+, r_{G1l}^+, r_{G1h}^-, r_{G1l}^-, W_h^{\text{spill}}, W_l^{\text{spill}}, \ell_{1h}^{\text{shed}}, \ell_{1l}^{\text{shed}}, \ell_{2h}^{\text{shed}}, \ell_{2l}^{\text{shed}} \geq 0.
\end{align*}
\]
Example

Uncoordinated market (UM)

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Powers in MW; costs in $/MWh

Pre-emptive market (PM)

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Powers in MW; costs in $/MWh
Example

Total system demand = 170 MW

- 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

Uncoordinated market (UM)

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Powers in MW; costs in $/MWh

Pre-emptive market (PM)

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Powers in MW; costs in $/MWh
Example

Min. \( 40r_{1h}^+ - 34r_{1h}^- + 200 (L_{1h}^{sh} + L_{2h}^{sh}) \)

s.t. \( r_{1h}^+ - r_{1h}^- + L_{1h}^{sh} + 50 - p_r^* - W_h^{sp} = - (\delta_{2h} - \delta_2^{0*}) / 0.13, \)

\( L_{2h}^{sh} = (\delta_{2h} - \delta_2^{0*}) / 0.13, \)

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

\( r_{1h}^+ \leq 100 - p_r^*, \quad r_{1h}^- \leq p_r^*, \)

\( L_{1h}^{sh} \leq 80; \quad L_{2h}^{sh} \leq 90, \)

\( W_h^{sp} \leq 50, \)

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

\( r_{1h}^+, \quad r_{1h}^-, \quad L_{1h}^{sh}, \quad L_{2h}^{sh}, \quad W_h^{sp} \geq 0, \)

Scenario “high”

Scenario “low”

Min. \( 40r_{1l}^+ - 34r_{1l}^- + 200 (L_{1l}^{sh} + L_{2l}^{sh}) \)

s.t. \( r_{1l}^+ - r_{1l}^- + L_{1l}^{sh} + 10 - p_r^* - W_l^{sp} = - (\delta_{2l} - \delta_2^{0*}) / 0.13, \)

\( L_{2l}^{sh} = (\delta_{2l} - \delta_2^{0*}) / 0.13, \)

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

\( r_{1l}^+ \leq 100 - p_r^*, \quad r_{1l}^- \leq p_r^*, \)

\( L_{1l}^{sh} \leq 80; \quad L_{2l}^{sh} \leq 90, \)

\( W_l^{sp} \leq 10, \)

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

\( r_{1l}^+, \quad r_{1l}^-, \quad L_{1l}^{sh}, \quad L_{2l}^{sh}, \quad W_l^{sp} \geq 0, \)
Total system demand = 170 MW

Uncoordinated market (UM)

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Powers in MW; costs in $/MWh

Pre-emptive market (PM)

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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.

Costly! (€200/MWh)
Dealing with Uncertain Supply
(Pre-emptive market)

Minimize $C^D(p_G, p_W) + E_\omega[C^B(y_\omega)]$

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

$p_W \leq \bar{W}$
$h^B(y_\omega, \delta_\omega, \delta^0) + W_\omega - p_W = 0, \ \forall \omega$
$g^B(y_\omega, \delta_\omega, p_G; W_\omega) \leq 0, \ \forall \omega$

$p^*_G, p^*_W, \delta^{0*}$

Balancing prognosis

Minimize $C^B(y_\omega')$

s.t. $h^B(y_\omega', \delta_\omega', \delta^{0*}) + W_\omega' - p^*_W = 0$
$g^B(y_\omega', \delta_\omega', p^*_G; W_\omega') \leq 0$

Minimize $C^D(p_G, p_W) + WC_\omega[C^B(y_\omega)]$

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

$p_W \leq \bar{W}$
$h^B(y_\omega, \delta_\omega, \delta^0) + W_\omega - p_W = 0, \ \forall \omega$
$g^B(y_\omega, \delta_\omega, p_G; W_\omega) \leq 0, \ \forall \omega$

$p^*_G, p^*_W, \delta^{0*}$

Worst-case scenario
Example

Total system demand = 170 MW

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<td>50</td>
</tr>
<tr>
<td>WP</td>
<td>34</td>
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</tbody>
</table>

Powers in MW; costs in $/MWh

Stochastic PM

<table>
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<th>$C$</th>
<th>$P^{\text{sch}}$</th>
</tr>
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<td>34</td>
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<td>10</td>
</tr>
</tbody>
</table>

Powers in MW; costs in $/MWh
## Example

### On average

<table>
<thead>
<tr>
<th>Unit</th>
<th>Total</th>
<th>Day ahead</th>
<th>Balancing</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>UM</td>
<td>3720</td>
<td>3080</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>SPM</td>
<td>3184</td>
<td>4000</td>
<td>-816</td>
<td>0</td>
</tr>
<tr>
<td>RPM</td>
<td>3800</td>
<td>3800</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### In scenario low (worst-case)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Total</th>
<th>Day ahead</th>
<th>Balancing</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>UM</td>
<td>4680</td>
<td>3080</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>SPM</td>
<td>4000</td>
<td>4000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RPM</td>
<td>3800</td>
<td>3800</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Scheduled production (MWh)

<table>
<thead>
<tr>
<th>Unit</th>
<th>UM</th>
<th>SPM</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>G2</td>
<td>86</td>
<td>70</td>
<td>110</td>
</tr>
<tr>
<td>G3</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>WP</td>
<td>34</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

### In scenario high (best-case)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Total</th>
<th>Day ahead</th>
<th>Balancing</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>UM</td>
<td>3080</td>
<td>3080</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SPM</td>
<td>2640</td>
<td>4000</td>
<td>-1360</td>
<td>0</td>
</tr>
<tr>
<td>RPM</td>
<td>3800</td>
<td>3800</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Prices & Revenues

\[
\begin{align*}
\text{Minimize} & \quad C^D(p_G, p_W) \\
\text{s.t.} & \quad h^D(p_G, p_W, \delta^0) - l = 0: \lambda^D \\
& \quad g^D(p_G, \delta^0) \leq 0 \\
& \quad p_W \leq \hat{W} \\
\end{align*}
\]

\[
\begin{align*}
\text{Minimize} & \quad C^B(y_{\omega'}) \\
\text{s.t.} & \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^0) + W_{\omega'} - p^*_W = 0: \lambda^B_{\omega'} \\
& \quad g^B(y_{\omega'}, \delta_{\omega'}, p^*_G; W_{\omega'}) \leq 0 \\
\end{align*}
\]

\[
\begin{align*}
\text{Minimize} & \quad C^D(p_G, p_W) + \mathbb{E}_\omega[C^B(y_{\omega})] \\
\text{s.t.} & \quad h^D(p_G, p_W, \delta^0) - l = 0: \lambda^D \\
& \quad g^D(p_G, \delta^0) \leq 0 \\
& \quad p_W \leq \bar{W} \\
& \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^0) + W_{\omega'} - p_W = 0, \quad \forall \omega \\
& \quad g^B(y_{\omega'}, \delta_{\omega'}, p_G; W_{\omega'}) \leq 0, \quad \forall \omega \\
\end{align*}
\]
Example

Total system demand = 170 MW

In “Stochastic PM” unit G1 is dispatched day ahead in a loss-making position

Uncoordinated market (UM)

<table>
<thead>
<tr>
<th>Unit</th>
<th>$P_{\text{max}}$</th>
<th>$C$</th>
<th>$P_{\text{sch}}$</th>
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Powers in MW; costs in $/MWh

Stochastic PM

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Powers in MW; costs in $/MWh
Total system demand = 170 MW

Uncoordinated market (UM)

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Powers in MW; costs in $/MWh

Stochastic PM

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Powers in MW; costs in $/MWh

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

Profit G1

<table>
<thead>
<tr>
<th>Unit</th>
<th>Expected</th>
<th>Per scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>UM</td>
<td>1320</td>
<td>High: (50 MW, 0.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low: (10 MW, 0.4)</td>
</tr>
<tr>
<td>Stoch PM</td>
<td>24</td>
<td>173.33</td>
</tr>
</tbody>
</table>

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

\[
\begin{align*}
\text{Minimize} & \quad C^D(p_G, p_W) \\
\text{s.t.} & \quad h^D(p_G, p_W, \delta^0) - l = 0 \\
& \quad g^D(p_G, \delta^0) \leq 0 \\
& \quad p_W \leq \hat{W}
\end{align*}
\]

Do we have something better than the expected production?

\[
\begin{align*}
\text{Minimize} & \quad C^B(y_{\omega'}) \\
\text{s.t.} & \quad h^B(y_{\omega'}, \delta_{\omega'}, \delta^{0*}) + W_{\omega'} - p^*_W = 0 \\
& \quad g^B(y_{\omega'}, \delta_{\omega'}, p^*_G, W_{\omega'}) \leq 0
\end{align*}
\]
Example
(Centralized dispatch of Stoch. Prod.)

Uncoordinated market (UM)

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Powers in MW; costs in $/MWh

Improved UM (IUM)

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<td>90</td>
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Powers in MW; costs in $/MWh
Example
(Centralized dispatch of Stoch. Prod.)

Uncoordinated market (UM)

<table>
<thead>
<tr>
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Powers in MW; costs in $/MWh

Improved

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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?

\[
\begin{align*}
\text{Minimize} & \quad C^D(p_G, p_W) + E_\omega \left[ C^B(y_\omega) \right] \\
\text{s.t.} & \quad h^B(y_\omega, \delta_\omega) + W_\omega - p_W = 0, \quad \forall \omega \\
& \quad g^B(y_\omega, \delta_\omega, p_G; W_\omega) \leq 0, \quad \forall \omega \\
& \quad 0 \leq p_W^{\text{max}} \leq W
\end{align*}
\]

\[
(p_G, p_W, \delta^0) \in \arg\left\{ \text{Minimize} \quad C^D(x_G, x_W) \right. \\
\text{s.t.} & \quad h^D(x_G, x_W, \theta) - l = 0 \\
& \quad g^D(x_G, \theta) \leq 0 \\
& \quad x_W \leq p_W^{\text{max}} \right\}
\]
Dealing with Uncertain Supply

Centralized dispatch of stochastic production

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

s.t. \[ r^-_{G_{1h}} - r^+_{G_{1h}} + l^h_{1h} + 50 - p_W - W^\text{spill}_h = \frac{(\delta^0_2 - \delta_{2h})}{0.13}, \]
\[ r^+_{G_{1l}} - r^-_{G_{1l}} + l^l_{1l} + 10 - p_W - W^\text{spill}_l = \frac{(\delta^0_2 - \delta_{2l})}{0.13}, \]
\[ l^h_{2h} = -\frac{(\delta^0_2 - \delta_{2h})}{0.13}, \]
\[ l^l_{2l} = -\frac{(\delta^0_2 - \delta_{2l})}{0.13}, \]
\[ p_{G_{1}} + r^+_{G_{1h}} \leq 100, \quad p_{G_{1}} + r^+_{G_{1l}} \leq 100, \]
\[ p_{G_{1}} - r^-_{G_{1h}} \geq 0, \quad p_{G_{1}} - r^-_{G_{1l}} \geq 0, \]
\[ -100 \leq \frac{\delta_{2h}}{0.13} \leq 100, \quad -100 \leq \frac{\delta_{2l}}{0.13} \leq 100, \]
\[ r^+_{G_{1h}} \leq 20, \quad r^+_{G_{1l}} \leq 20, \]
\[ r^-_{G_{1h}} \leq 40, \quad r^-_{G_{1l}} \leq 40, \]
\[ W^\text{spill}_h \leq 50, \quad W^\text{spill}_l \leq 10, \]
\[ l^h_{1h} \leq 80, \quad l^l_{1l} \leq 80, \quad l^h_{2h} \leq 90, \quad l^l_{2l} \leq 90, \]
\[ r^+_{G_{1h}}, \, r^+_{G_{1l}}, \, r^-_{G_{1h}}, \, r^-_{G_{1l}}, \, W^\text{spill}_h, \, W^\text{spill}_l, \, l^h_{1h}, \, l^l_{1l}, \, l^h_{2h}, \, l^l_{2l} \geq 0, \]
\[ 0 \leq p_W^\text{max} \leq 50. \]

$\left(p_{G_{1}}, \, p_{G_{2}}, \, p_{G_{3}}, \, p_W, \, \delta^0_2\right) \in \arg \min_{x_{G_{1}}, \, x_{G_{2}}, \, x_{G_{3}}, \, x_W, \, \theta} \quad 35x_{G_{1}} + 30x_{G_{2}} + 10x_{G_{3}}$

s.t. $x_{G_{1}} + x_{G_{2}} + x_W - 80 = -\frac{\theta}{0.13} : z^D_1,$
\[ x_{G_{3}} - 90 = \frac{\theta}{0.13} : z^D_2, \]
\[ x_{G_{1}} \leq 100 : \mu_{G_{1}}, \quad x_{G_{2}} \leq 110 : \mu_{G_{2}}, \quad x_{G_{3}} \leq 50 : \mu_{G_{3}}, \]
\[ -100 \leq \frac{\theta}{0.13} \leq 100 : \left(\mu_{\theta}, \bar{\mu}_{\theta}\right), \]
\[ x_{W} \leq p_W^\text{max} : \bar{\rho}, \]
\[ x_{G_{1}}, \, x_{G_{2}}, \, x_{G_{3}}, \, x_W \geq 0 : \left(\mu_{G_{1}}, \, \mu_{G_{2}}, \, \mu_{G_{3}}, \, \bar{\rho}\right). \]
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 $\rho$
• 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

<table>
<thead>
<tr>
<th>Wind penetration 38% ( \rho = 0.35 )</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>1</td>
<td>6</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Expected profit ($)</td>
<td>47.9</td>
<td>49.4</td>
<td>102.2</td>
<td>67.4</td>
</tr>
<tr>
<td>Average losses ($)</td>
<td>–14.9</td>
<td>–10.7</td>
<td>–16.5</td>
<td>–9.7</td>
</tr>
<tr>
<td>Probability profit &lt; 0</td>
<td><strong>0.81</strong></td>
<td>0.71</td>
<td>0.71</td>
<td>0.75</td>
</tr>
<tr>
<td>Stoch PM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UM</td>
<td>Expected profit ($)</td>
<td>379.8</td>
<td>359.7</td>
<td>724.9</td>
</tr>
<tr>
<td>IUM</td>
<td>Expected profit ($)</td>
<td>170.2</td>
<td>263.7</td>
<td>531.6</td>
</tr>
</tbody>
</table>
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:


http://arxiv.org/abs/1507.06092

✓ Risk-neutral virtual bidder:

\[
\begin{align*}
\text{Maximize} & \quad p_V \lambda^D + \int_{\Omega} \Delta p_V \lambda^B(\omega) f(\omega) d\omega \\
\text{s.t.} & \quad p_V + \Delta p_V = 0
\end{align*}
\]
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
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?