Congestion Management in a Stochastic Dispatch Model for Electricity Markets

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Reasons for inadequate congestion handling:

• Congestion within areas not considered (in full)
• «Loop-flow» not included in market clearing
• Inadequate representation of capacity constraints
Figure 2. Power generation by power source in the Nordic region in 2013

- Hydro: 203 TWh (53%)
- Nuclear: 86 TWh (23%)
- Fossil: 47 TWh (12%)
- Biomass: 23 TWh (6%)
- Wind: 24 TWh (6%)

Source: ENTSO-E
### Table 13. Nordic Generation capacity (MW) by power source, 2013

<table>
<thead>
<tr>
<th></th>
<th>Denmark</th>
<th>Finland</th>
<th>Norway</th>
<th>Sweden</th>
<th>Nordic region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed capacity (total)</td>
<td>14,861</td>
<td>17,300</td>
<td>32,879</td>
<td>38,273</td>
<td>103,313</td>
</tr>
<tr>
<td>Nuclear power</td>
<td>-</td>
<td>2,752</td>
<td>-</td>
<td>9,531</td>
<td>12,283</td>
</tr>
<tr>
<td>Other thermal power</td>
<td>6,989</td>
<td>11,135</td>
<td>1,040</td>
<td>8,079</td>
<td>27,243</td>
</tr>
<tr>
<td>- Condensing power</td>
<td>-</td>
<td>2,465</td>
<td>-</td>
<td>1,375</td>
<td>3,840</td>
</tr>
<tr>
<td>- CHP, district heating</td>
<td>1,929</td>
<td>4,375</td>
<td>-</td>
<td>3,631</td>
<td>9,935</td>
</tr>
<tr>
<td>- CHP, industry</td>
<td>562</td>
<td>3,180</td>
<td>-</td>
<td>1,498</td>
<td>5,240</td>
</tr>
<tr>
<td>- Gas turbines etc.</td>
<td>-</td>
<td>1,115</td>
<td>-</td>
<td>1,575</td>
<td>2,690</td>
</tr>
<tr>
<td>Hydro power</td>
<td>9</td>
<td>3,125</td>
<td>30,900</td>
<td>16,150</td>
<td>50,184</td>
</tr>
<tr>
<td>Wind power</td>
<td>4,809</td>
<td>288</td>
<td>811</td>
<td>3,745</td>
<td>9,653</td>
</tr>
<tr>
<td>Sun power</td>
<td>563</td>
<td>0</td>
<td>N/A</td>
<td>43</td>
<td>606</td>
</tr>
</tbody>
</table>

Source: Swedenergy, NVE, DERA, EMI
Nord Pool Spot - 2015/01/12, 18-19
Towards Single European Market: 
Next Steps

- Markets included in PCR - over 2800 TWh of yearly consumption
- Markets associate members of PCR
- Markets that could join next as part of an agreed European roadmap
Markets and systems for:

- **Real-time balancing** (Regulating power market, and other ancillary services)
- **Congestion alleviation**
Flexibility costs and uncertainty

- High uncertainty
- Low uncertainty

Flexibility costs: extra adjustment costs
e.g. due to
- resetting plans,
- non-optimal operation,
- more expensive units
- rules of the auction

Day-ahead market | Regulation market | Delivery hour (e.g. 08:00-08:59)
Stochastic market clearing

- Literature:
  - Wong and Fuller (2007); Bouffard et al. (2005b,a); Pritchard et al. (2010); Khazaei et al. (2012); Morales et al. (2012); Khazaei et al. (2013, 2014a,b); Morales et al. (2014); Zugno and Conejo (2013) ...

- Our paper:
  - Energy-only stochastic market clearing as in Pritchard et al. (2010)
  - How should the day-ahead part of the market be modeled?
    - Effects of day-ahead network flow and balance constraints
  - Compare to a sequential market clearing model with myopic clearing of the day-ahead part of the market
Day-ahead and real-time generation ($\geq 0$) and load ($\leq 0$) quantities:

$$x_i \in C^1_i \quad \forall i \in I$$
$$X_{i\omega} \in C^2_i(\omega, x_i) \quad \forall i \in I, \ \omega \in \Omega$$

Upregulation $X_{i\omega}^u = \max\{X_{i\omega} - x_i, 0\}$ or downregulation $X_{i\omega}^d = \max\{x_i - X_{i\omega}, 0\}$ for flexible entities.
Generator cost functions

\[ a_i + b_i x_i \]

\[ a_i - a_i^{d} \]

\[ b_i \]

\[ b_i^{d} \]
Load benefit curves

\[ a_i + b_i x_i \]

\[ a_i - a_i^d \]

\[ b_i \]

\[ b_i^u \]

\[ a_i^u - a_i \]

\[ X_{i \omega_1} \]

\[ X_{i \omega_2} \]
Objective function

Cost of real-time quantity at day-ahead parameters:

\[ c_i(X_{i\omega}) = a_i X_{i\omega} + 0.5b_i(X_{i\omega})^2 \]

Flexibility cost:

\[ \tilde{c}_i(x_i, X_{i\omega}) = (a_i^u - a_i)X_{i\omega}^u + 0.5(b_i^u - b_i)(X_{i\omega}^u)^2 \\
+ (a_i - a_i^d)X_{i\omega}^d + 0.5(b_i^d - b_i)(X_{i\omega}^d)^2 \]
Stochastic market clearing model

\[
\min_{x, f, X, F} \mathbb{E} \left[ \sum_{i \in I} \left( c_i(X_i) + \tilde{c}_i(x_i, X_i) \right) \right] \tag{1a}
\]

s.t.
\[
\begin{align*}
\forall i \in I & : x_i \in C_i^1 \tag{1b} \\
\forall i \in I, \omega \in \Omega & : X_{i\omega} \in C_i^2(\omega, x_i) \tag{1c} \\
\forall n \in N & : \tau_n(f) + \sum_{i \in I(n)} x_i = 0 \tag{1d} \\
\forall n \in N, \omega \in \Omega & : \tau_n(F_\omega) - \tau_n(f) + \sum_{i \in I(n)} (X_{i\omega} - x_i) = 0 \tag{1e} \\
\forall \omega \in \Omega & : f \in U^1 \tag{1f} \\
\forall \omega \in \Omega & : F_\omega \in U^2 \tag{1g}
\end{align*}
\]
Myopic market clearing model - day-ahead part

\[
\begin{align*}
\min_{x,f} & \quad \sum_{i \in I} c_i(x_i) \quad (2a) \\
\text{s.t.} & \quad x_i \in C_i^1 \quad \forall i \in I \quad (2b) \\
& \quad \tau_n(f) + \sum_{i \in I(n)} x_i = 0 \quad \forall n \in N \quad [\pi_n] \quad (2c) \\
& \quad f \in U^1 \quad (2d)
\end{align*}
\]
Myopic market clearing model - real-time part, scenario $\omega$

\[
\min_{X_\omega,F_\omega} \sum_{i \in I} \left( c_i(X_i\omega) + \tilde{c}_i(x_i,X_i\omega) \right)
\]
\[
\text{s.t.}
\]
\[
X_i\omega \in C_i^2(\omega,x_i) \quad \forall i \in I
\]
\[
\tau_n(F_\omega) - \tau_n(f) + \sum_{i \in I(n)} (X_i\omega - x_i) = 0 \quad \forall n \in N \quad [p_\omega\lambda_{n\omega}]
\]
\[
F_\omega \in U^2
\]
Day-ahead constraints

- We assume that $U^2$ represents the network constraints in a DC load flow model without losses
- What should $U^1$ represent?
Alternative day-ahead network representations

1. Nodal model, i.e., $U^1 = U^2$
2. Zonal model
   - No loop flow
   - Aggregate flow capacities set by system operator(s)
3. Unconstrained flow, i.e., $U^1 = \mathbb{R}^{|L|}$
4. Unconstrained flow and balance

$$\min[v_{nodi}^{stoch}, v_{zonal}^{stoch}] \geq v_{bal}^{stoch} \geq v_{unc}^{stoch}$$
Example 1

- \( P(1) = P(2) = 0.5 \)
- Real-time quantities \( X_\omega \) are given above
- All cost parameters equal zero, except \( a_1^u = a_2^u = 1 \) and \( a_3^u = 0.25 \)
- All lines have identical impedances
- Capacity of line (2,3) is 40
Example 1 - stochastic model

\[
\begin{align*}
\text{min } & \quad 0.5 \cdot 1 \cdot ([30 - x_1]^+ + [0 - x_1]^+ + [0 - x_3]^+ + [60 - x_3]^+) \\
& \quad + 0.5 \cdot 0.25 \cdot ([-30 - x_3]^+ + [-60 - x_3]^+) \\
\text{s.t.} & \quad x_1 + x_2 + x_3 = 0 \\
& \quad -40 \leq \frac{x_2 - x_3}{3} \leq 40
\end{align*}
\]
Example 1 - optimal day-ahead schedules

\[ v_{\text{unc}}^{\text{stoch}} = 0 \]

\[ v_{\text{bal}}^{\text{stoch}} = 0.5 \cdot (-30 - (-90)) \cdot 0.25 + 0.5 \cdot (-60 - (-90)) \cdot 0.25 = 11.25 \]

\[ v_{\text{nodal}}^{\text{stoch}} = 0.5 \cdot (-30 - (-75)) \cdot 0.25 + 0.5 \cdot [60 - 45] \cdot 1 + (-60 - (-75)) \cdot 0.25 = 15 \]
Example 2

**Node 2: Nuclear + Thermal**

- Euros/MWh: 0, 10000, 15000
- MWh/h: 0, 10000, 15000

**Node 1: Wind (scen. 2) – Consumption**

- Euros/MWh: 0, 7000, 150
- MWh/h: 0, 2000, 3000

**Node 3: Hydro**

- Euros/MWh: 0, 150
- MWh/h: 0, 15000

\[ b = 0.01 \]
Wind scenarios

- $p_1 = 0.2$
- $p_2 = 0.5$
- $p_3 = 0.3$

- Wind = 0
- Wind = 7000
- Wind = 15000
### Cost and benefit parameters

<table>
<thead>
<tr>
<th>Entity</th>
<th>Node</th>
<th>Intercept ($a$)</th>
<th>Slope ($b$)</th>
<th>Flexible?</th>
<th>Flex. cost up</th>
<th>Flex. cost down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Partly</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Load</td>
<td>1</td>
<td>150</td>
<td>0.01</td>
<td>Yes</td>
<td>$b^u = 30b$</td>
<td>-</td>
</tr>
<tr>
<td>Nucl.</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>No</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Therm.</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>Yes</td>
<td>$a^u - a = 6$</td>
<td>-</td>
</tr>
<tr>
<td>Hydro</td>
<td>3</td>
<td>0</td>
<td>0.01</td>
<td>Yes</td>
<td>$b^u = 10b$</td>
<td>-</td>
</tr>
</tbody>
</table>
## Example 2 - optimal values, stochastic model

<table>
<thead>
<tr>
<th>Model</th>
<th>Value (1000 €s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wait-and-see</td>
<td>956.620</td>
</tr>
<tr>
<td>Unconstrained</td>
<td>952.500</td>
</tr>
<tr>
<td>Balanced</td>
<td>950.808</td>
</tr>
<tr>
<td>Nodal</td>
<td>950.542</td>
</tr>
<tr>
<td>Zonal ((cap_{{1},{2,3}} = 3000))</td>
<td>938.986</td>
</tr>
<tr>
<td>Zonal ((cap_{{1},{2,3}} = 5000))</td>
<td>950.808</td>
</tr>
</tbody>
</table>
Example 2 - optimal schedules, stochastic model

### Nodal model

<table>
<thead>
<tr>
<th>Entity</th>
<th>Day-head</th>
<th>Real-time adj.</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>0</td>
<td>7000</td>
<td>13800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nucl.</td>
<td>1200</td>
<td>-42</td>
<td>438</td>
<td>-42</td>
<td></td>
</tr>
<tr>
<td>Therm.</td>
<td>42</td>
<td>83</td>
<td>-877</td>
<td>-3517</td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>3517</td>
<td>-42</td>
<td>-6562</td>
<td>-10242</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>-4758</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0</strong></td>
<td><strong>0</strong></td>
<td><strong>0</strong></td>
<td><strong>0</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Power flow - nodal model**

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### Unconstrained model

<table>
<thead>
<tr>
<th>Entity</th>
<th>Day-head</th>
<th>Real-time adj.</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>0</td>
<td>7000</td>
<td>14000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nucl.</td>
<td>1000</td>
<td>-800</td>
<td>-800</td>
<td>-800</td>
<td></td>
</tr>
<tr>
<td>Therm.</td>
<td>800</td>
<td>800</td>
<td>-800</td>
<td>-800</td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>4000</td>
<td>1200 (−42)</td>
<td>1680 (438)</td>
<td>-4000</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>-5000</td>
<td>2800 (42)</td>
<td>3600 (83)</td>
<td>-3517</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>800</td>
<td>-800</td>
<td>-800</td>
<td>-800</td>
<td></td>
</tr>
</tbody>
</table>
## Example 2 - cost and benefit effects, stochastic model

### Nodal model

<table>
<thead>
<tr>
<th>Entity</th>
<th>(E[-c])</th>
<th>Flex. costs ((\bar{c}))</th>
<th>(E[-c - \bar{c}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>0.000</td>
<td>Low: -2.400 Medium: -2.630</td>
<td>High: 0.000</td>
</tr>
<tr>
<td>Nuc.</td>
<td>-2.400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Therm.</td>
<td>-2.400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>-30.384</td>
<td>-0.313</td>
<td>-30.447</td>
</tr>
<tr>
<td>Load</td>
<td>987.104</td>
<td></td>
<td>987.104</td>
</tr>
<tr>
<td>Total</td>
<td>951.920</td>
<td>-0.313</td>
<td>-2.630 -0.000</td>
</tr>
</tbody>
</table>

### Unconstrained model

<table>
<thead>
<tr>
<th>(E[-c])</th>
<th>Flex. costs ((\bar{c}))</th>
<th>(E[-c - \bar{c}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>Low: -2.000 Medium: -4.000</td>
<td>High: 0.000</td>
</tr>
<tr>
<td>-2.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-30.400</td>
<td>-30.400</td>
<td></td>
</tr>
<tr>
<td>988.900</td>
<td>988.900</td>
<td></td>
</tr>
<tr>
<td>952.500</td>
<td>0.000 0.000 0.000 0.000</td>
<td>952.500</td>
</tr>
</tbody>
</table>
Myopic model

- Infeasibility issue, e.g. due to scheduling of non-flexible nuclear in day-ahead market
Myopic / nodal model - effect of day-ahead wind capacity
Conclusions and further research

- Too restrictive constraints in the day-ahead stage of a stochastic market clearing model may hinder flexibility and yield sub-optimal solutions.
- Examples of such constraints are DC load flow capacities, European-style zonal capacities, and even nodal balance constraints.
- Further research:
  - Pricing
  - Investigate relevance for deterministic (sequential) market clearing models
References


