Impact of Forecast errors on Generation and Transmission Expansion Planning

Workshop on Mathematical Models and Methods for Energy Optimization (Budapest)

Salvador Pineda ¹  Juan M. Morales ²  Trine K. Boomsma ¹

¹University of Copenhagen, funded by FEMs project (www.futureelmarket.dk)
²Technical University of Denmark, funded by CITIES project (www.smart-cities-centre.org)

September, 25, 2014
Energy systems

- A **power system** is a network of electrical components used to supply, transmit and use electric power.
- Electricity cannot be **stored**: generation = demand.
- Increase in production by **renewable** sources: new challenges.

![Graph showing wind penetration in various countries]

*Source: Berkeley Lab estimates based on data from Navigant, EIA, and elsewhere.*
Wind power production

- Wind power production **varies** through time
- Wind power production is **hard to predict** in advance

Demand DK2 (12/08/14)

Wind DK2 (12/08/14)
We were wondering...

- How can we account for forecast errors within current generation and transmission capacity expansion models?

- What is the impact of these forecast errors on generation and transmission capacity expansion planning?

- What is the impact of the market design on generation and transmission capacity expansion planning?
Some assumptions

- Static expansion models (single target year)
- Focus on short-term uncertainties (scenarios)
- No inter-temporal constraints (stationary process)
- Energy-only market with marginal pricing
- Perfect competitive market
- Convex production cost functions
- Inelastic demand
- DC representation of the network
Two markets floors

Day-ahead market
(24 hours before operation)

Balancing market
(30 minutes before operation)
Coordination between the two market floors

Inefficient market

Day-ahead: \( \min C^D(\Phi^D) \)

Balancing: \( \min C^B(\Phi^D, \Phi^B) \)

- Cheapest day-ahead
- Expensive balancing
- High total cost
- Reserves after energy

Efficient market

Day-ahead + balancing

\( \min C^D(\Phi^D) + \sum_r \pi_r C^B(\Phi^D, \Phi^B) \)

- More expensive day-ahead
- Cheaper balancing
- Minimum total cost
- Simultaneous reserve and energy
We have investigated

- The impact of forecast errors on GE of stochastic units by a central planner:
  - Central GEP without forecast errors
  - Central GEP with forecast errors under efficient market
  - Central GEP with forecast errors under inefficient market

- How a collusion of producers affects the GE of stochastic units:
  - Collusion GEP without forecast errors
  - Collusion GEP with forecast errors under efficient market
  - Collusion GEP with forecast errors under inefficient market

- The impact of forecast errors on G&T expansion by a central planner:
  - G&TEP without forecast errors
  - G&TEP with forecast errors under efficient market
  - G&TEP with forecast errors under inefficient market
Central GEP without forecast errors

\[
\begin{align*}
\text{Min} & \quad \sum_s \tau_s C^D (\Phi^D_s) + C^I (\overline{p}_W^s) \\
\text{s.t.} & \quad f (\overline{p}_W^s) \leq 0 \\
& \quad h^D (\Phi^D_s; l_s) = 0, \quad \forall s \\
& \quad g^D (\overline{p}_W^s, \Phi^D_s; \rho_s) \leq 0, \quad \forall s.
\end{align*}
\]

- $\overline{p}_W^s$: capacity to be installed
- $\Phi^D_s$: dispatch decisions
- $\rho_s$: capacity factor of stochastic units
Central GEP with forecast errors under efficient market

\[
\begin{align*}
\text{Min} & \quad \bar{p}^W, \Phi^D_s, \Phi^B_{sr} \quad \sum_s \tau_s \left( C^D (\Phi^D_s) + \sum_r \pi_{sr} C^B (\Phi^B_{sr}) \right) + C^I (\bar{p}^W) \\
\text{s.t.} & \quad f (\bar{p}^W) \leq 0 \\
& \quad h^D (\Phi^D_s; l_s) = 0, \quad \forall s \\
& \quad g^D (\bar{p}^W, \Phi^D_s; \rho_s) \leq 0, \quad \forall s \\
& \quad h^B (\Phi^B_{sr}) = 0, \quad \forall s, \forall r \\
& \quad g^B (\bar{p}^W, \Phi^D_s, \Phi^B_{sr}; \rho_s, \Delta \rho_{sr}) \leq 0, \quad \forall s, \forall r.
\end{align*}
\]

$\Phi^B_{sr}$ re-dispatch decisions

$\Delta \rho_{sr}$ variation of capacity factor
Central GEP with forecast errors under inefficient market

\[
\begin{align*}
\text{Min} & \quad \bar{p}^W, \Phi^D_s, \Phi^B_{sr} \left( \sum_s \tau_s \left( C^D (\Phi^D_s) + \sum_r \pi_{sr} C^B (\Phi^B_{sr}) \right) + C^I (\bar{p}^W) \right) \\
\text{s.t.} & \quad f (\bar{p}^W) \leq 0 \\
& \quad h^B (\Phi^B_{sr}) = 0, \quad \forall s, \forall r \\
& \quad g^B (\bar{p}^W, \Phi^D_s, \Phi^B_{sr}; \rho_s, \Delta \rho_{sr}) \leq 0, \quad \forall s, \forall r \\
\Phi^D_s & \in \arg \left\{ \begin{array}{l}
\text{Min} \\
C^D (\Phi^D_s)
\end{array} \right. \\
\text{s.t.} & \quad h^D (\Phi^D_s; l_s) = 0 \\
& \quad g^D (\bar{p}^W, \Phi^D_s; \rho_s) \leq 0.
\end{align*}
\]

Impose cost merit-order at the day-ahead
Data of illustrative example

- Four 100-MW inflexible blocks with marginal costs 20, 21, 22, 23
- Two 100-MW flexible blocks with marginal costs 24, 25
- A constant load of 400 MW and no network
- Expansion of one hundred 5-MW units with a cost of $430000
- Two time segments: $\rho_{s1} = 0.2$ and $\rho_{s2} = 0.8$
- Four equiprobable scenarios for forecast errors:

$$
\Delta \rho_{s1r1} = -0.07 \quad \Delta \rho_{s1r2} = -0.02 \quad \Delta \rho_{s1r3} = 0.02 \quad \Delta \rho_{s1r4} = 0.08 \\
\Delta \rho_{s2r1} = -0.26 \quad \Delta \rho_{s2r2} = -0.02 \quad \Delta \rho_{s2r3} = 0.10 \quad \Delta \rho_{s2r4} = 0.18
$$
## Generation expansion under perfect competition

<table>
<thead>
<tr>
<th></th>
<th>$\bar{p}$ (MW)</th>
<th>$C^I$ ($M$)</th>
<th>$C^D$ ($M$)</th>
<th>$C^B$ ($M$)</th>
<th>$\bar{C}$ ($M$)</th>
<th>$\psi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No errors</td>
<td>410</td>
<td>35.26</td>
<td>35.82</td>
<td>0.00</td>
<td>71.08</td>
<td>51.25</td>
</tr>
<tr>
<td>Efficient</td>
<td>360</td>
<td>30.96</td>
<td>42.35</td>
<td>-0.83</td>
<td>72.48</td>
<td>45.02</td>
</tr>
<tr>
<td>Inefficient</td>
<td>250</td>
<td>21.50</td>
<td>50.58</td>
<td>2.45</td>
<td>74.54</td>
<td>28.34</td>
</tr>
</tbody>
</table>

- Without forecast errors we get the highest capacity and wind share
- Forecast errors reduce the installed capacity and the wind share
- An efficient market designs soften the adverse effects of forecast errors
Collusion GEP without forecast errors

\[
\begin{align*}
\text{Max} & \quad \sum_s \tau_s \Pi^D (\Phi_s^D, \lambda_s^D) - C^I (\bar{p}^W) \\
\text{s.t.} & \quad f (\bar{p}^W) \leq 0
\end{align*}
\]

\[
(\Phi_s^D, \lambda_s^D) \in \arg \left\{ \begin{array}{l}
\text{Min} \quad C^D (\Phi_s^D) \\
\text{s.t.} \quad h^D (\Phi_s^D; l_s) = 0: \lambda_s^D \\
\quad g^D (\bar{p}^W, \Phi_s^D; \rho_s) \leq 0 \end{array} \right\} \quad \forall s
\]

\(\Pi^D\) revenue in the day-ahead market

\(\lambda_s^D\) day-ahead price
Collusion GEP with forecast errors under efficient market

\[
\begin{align*}
\text{Max} & \quad \frac{\Pi^D \left( \Phi^D_s, \lambda^D_s \right)}{p^W} + \sum_r \pi_{sr} \frac{\Pi^B \left( \Phi^B_{sr}, \lambda^B_{sr} \right)}{p^W} - C^I \left( \overline{p}^W \right) \\
\text{s.t.} & \quad f (\overline{p}^W) \leq 0 \\
\left( \Phi^D_s, \lambda^D_s, \Phi^B_{sr}, \lambda^B_{sr} \right) & \in \arg \left\{ \begin{array}{l}
\text{Min} \frac{C^D \left( \Phi^D_s \right)}{\Phi^D_s, \Phi^B_{sr}} + \sum_r \pi_{sr} C^B \left( \Phi^B_{sr} \right) \\
\text{s.t.} & \quad h^D \left( \Phi^D_s, l_s \right) = 0 : \lambda^D_s \\
& \quad g^D \left( \overline{p}^W, \Phi^D_s, \rho_s \right) \leq 0 \\
& \quad h^B \left( \Phi^B_{sr} \right) = 0 : \pi_{sr} \lambda^B_{sr}, \quad \forall r \\
& \quad g^B \left( \overline{p}^W, \Phi^D_s, \Phi^B_{sr}, \rho_s, \Delta \rho_{sr} \right) \leq 0, \quad \forall r
\end{array} \right\} \forall s
\end{align*}
\]

\( \Pi^B \) revenue in the balancing market  
\( \lambda^B_{sr} \) balancing price
Collusion GEP with forecast errors under inefficient market

\[
\begin{align*}
\text{Max} & \quad \frac{1}{p^W} \sum_s \tau_s \left( \Pi^D (\Phi^D_s, \lambda^D_s) + \sum_r \pi_{sr} \Pi^B (\Phi^B_{sr}, \lambda^B_{sr}) \right) - C^I (p^W) \\
\text{s.t.} & \quad f (p^W) \leq 0
\end{align*}
\]

\[(\Phi^D_s, \lambda^D_s) \in \arg\min_{\Phi^D_s} \begin{cases} 
\text{Min} & \quad C^D (\Phi^D_s) \\
\text{s.t.} & \quad h^D (\Phi^D_s; l_s) = 0 : \lambda^D_s \\
& \quad g^D (p^W, \Phi^D_s; \rho_s) \leq 0
\end{cases} \forall s
\]

\[(\Phi^B_{sr}, \lambda^B_{sr}) \in \arg\min_{\Phi^B_{sr}} \begin{cases} 
\text{Min} & \quad C^B (\Phi^B_{sr}) \\
\text{s.t.} & \quad h^B (\Phi^B_{sr}) = 0 : \lambda^B_{sr} \\
& \quad g^B (p^W, \Phi^D_s, \Phi^B_{sr}; \rho_s, \Delta \rho_{sr}) \leq 0
\end{cases} \forall sr.
\]
Collusion GEP with forecast errors under inefficient market

\[
\begin{align*}
\text{Max} & \quad \sum_s \pi_s \left( \Pi^D \left( \Phi^D_s, \hat{\lambda}^D_s \right) + \sum_r \pi_{sr} \Pi^B \left( \Phi^B_{sr}, \lambda^B_{sr} \right) \right) - C^I \left( \bar{p}^W \right) \\
\text{s.t.} & \quad f \left( \bar{p}^W \right) \leq 0 \\
\left( \Phi^D_s, \lambda^D_s, \Phi^B_{sr}, \lambda^B_{sr} \right) & \in \text{arg} \left\{ \begin{array}{l}
\text{Min} \quad C^D \left( \Phi^D_s \right) + \sum_r \pi_{sr} C^B \left( \Phi^B_{sr} \right) \\
\text{s.t.} & \quad h^B \left( \Phi^B_{sr} \right) = 0 : \pi_{sr} \lambda^B_{sr} \\
& \quad g^B \left( \bar{p}^W, \Phi^D_s, \Phi^B_{sr}; \rho_s, \Delta \rho_{sr} \right) \leq 0 \\
\Phi^D_s & \in \text{arg} \left\{ \begin{array}{l}
\text{Min} \quad C^D \left( \Phi^D_s \right) \\
\text{s.t.} & \quad h^D \left( \Phi^D_s; l_s \right) = 0 : \hat{\lambda}^D_s \\
& \quad g^D \left( \bar{p}^W, \Phi^D_s; \rho_s \right) \leq 0 \end{array} \right\} \forall s
\end{array} \right.
\end{align*}
\]
### Generation expansion under imperfect competition

<table>
<thead>
<tr>
<th></th>
<th>Perfect competition</th>
<th></th>
<th>Collusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \bar{p} ) (MW)</td>
<td>( \bar{C} ) ($M)</td>
<td>( \psi ) (%)</td>
</tr>
<tr>
<td>No errors</td>
<td>410</td>
<td>71.08</td>
<td>51.25</td>
</tr>
<tr>
<td>Efficient</td>
<td>360</td>
<td>72.48</td>
<td>45.02</td>
</tr>
<tr>
<td>Inefficient</td>
<td>250</td>
<td>74.54</td>
<td>28.34</td>
</tr>
</tbody>
</table>

- Under a collusion the installed capacities decrease
- Forecast errors reduce the capacity and the wind share
- An efficient market designs soften the adverse effects of forecast errors
Generation and transmission expansion models

- Investment decisions made by a central planner
- New stochastic and conventional generation
- New transmission lines
- Day-ahead and a balancing market
- Forecast errors of load and wind production
- Efficient and inefficient market design
Generation and transmission expansion models

- 24-bus system (IEEE)
- 10 existing conventional units
- 3 flexible generating units
- Variable demand
- 4 projects of stochastic units
- 3 new flexible generating units
- 7 new transmission lines
- Renewable target of 20/30/40%
### G&T expansion for 20% renewable target

<table>
<thead>
<tr>
<th></th>
<th>No errors</th>
<th>Efficient</th>
<th>Inefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind capacity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_6$</td>
<td>-</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>$n_8$</td>
<td>950</td>
<td>1000</td>
<td>900</td>
</tr>
<tr>
<td>$n_{13}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$n_{23}$</td>
<td>400</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td><strong>Flexible Generation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_{18}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$n_{21}$</td>
<td>-</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>$n_{22}$</td>
<td>-</td>
<td>-</td>
<td>160</td>
</tr>
<tr>
<td><strong>Line capacity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_{6}n_{10}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$n_{8}n_{9}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$n_{11}n_{13}$</td>
<td>175</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>$n_{11}n_{14}$</td>
<td>-</td>
<td>-</td>
<td>175</td>
</tr>
<tr>
<td>$n_{12}n_{21}$</td>
<td>-</td>
<td>350</td>
<td>-</td>
</tr>
<tr>
<td>$n_{12}n_{23}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$n_{14}n_{16}$</td>
<td>-</td>
<td>-</td>
<td>175</td>
</tr>
<tr>
<td><strong>Investment cost</strong></td>
<td>162.6</td>
<td>165.1</td>
<td>172.8</td>
</tr>
</tbody>
</table>
# Impact of forecast errors on G&T expansion

<table>
<thead>
<tr>
<th>Market</th>
<th>Expansion</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficient</td>
<td>Errors</td>
<td>474.8(20)</td>
<td>527.8(30)</td>
<td>589.2(40)</td>
</tr>
<tr>
<td></td>
<td>No errors</td>
<td>475.5(19.2)</td>
<td>530.7(26.5)</td>
<td>587.7(31.5)</td>
</tr>
<tr>
<td>Inefficient</td>
<td>Errors</td>
<td>484.2(20)</td>
<td>543.6(30)</td>
<td>607.8(40)</td>
</tr>
<tr>
<td></td>
<td>No errors</td>
<td>526.5(19.3)</td>
<td>631.7(28.7)</td>
<td>728.2(36.1)</td>
</tr>
</tbody>
</table>

- Under an efficient market, disregarding the errors will entail a reduction of the renewable target.
- Under an inefficient market, disregarding the errors will entail a significant increase of the cost.
Conclusions

- We have presented a set of generation and transmission expansion models that account for the forecast errors of stochastic production.

- These models can be reformulated as single-level mixed-integer linear or non-linear programming problems.

- Considering production forecast errors impacts the expansion plans for the generation and transmission of power systems.

- An efficient market design softens the negative effects of forecast errors and leads to cheaper expansion plans and higher penetration levels of renewable production.

- The consequences of an expansion plan determined under an error-free assumption highly depend on the market design.
Future research

- Model intermediate situations at the investment level between perfect competition and collusion

- Model intermediate market designs between the paradigmatic efficient and inefficient

- Model the exercise of market power by the producers when offering in the electricity market

- Apply dedicated computational methods to improve tractability of the multi-year case
Thanks for the attention!

Questions?

Website: https://sites.google.com/site/slv2pm/