Long-term Effects of Congestion Management – Modeling Framework and Large Scale Application

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Outline

1. Background, literature and contribution

2. Economic framework

3. Large scale application

4. Conclusions
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3. Large scale application
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Background

• In *liberalized* power systems, generation and transmission services are necessarily *unbundled*…
• … but remain tightly *interlinked*
  – e.g., TSOs influenced by level and locality of generation and load
  – e.g., generating firms impacted by trade restrictions

→ Congestion management in the transmission network is of crucial importance for the efficiency of those inter-linkages
Literature

• Different designs have been suggested, analyzed and followed (e.g. uniform zonal pricing with redispatch or nodal pricing)
• Literature has either focused on short-term efficiency of congestion management or specific issues of timing investments
Contributions

• Generalized and flexible *economic modeling framework* based to capture generation, transmission, and their inter-linkages

• Consistent analysis of *short and long-term effects* of different congestion management designs
  – Identification and isolation of *frictions* and sources of *inefficiencies* inherent to the different designs
  – *Comparative analysis* including a *benchmark* against the first-best welfare-optimal result

• Calibration and numerical solution for a detailed representation of the CWE region, consisting of 70 nodes and 174 power lines; Analysis of six relevant congestion management designs until 2030
Outline

1. Background, literature and contribution
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3. Large scale application
4. Conclusions
Dimensions of designing congestion management

1st dimension: market area

Nodal versus Zonal
Dimensions of designing congestion management

2nd dimension: short-term TSO measures

Redispatch versus G-component
Dimensions of designing congestion management

3rd dimension: degree of coordination between TSOs

National versus Cross-border
## Dimensions of designing congestion management

### Settings covered by our analysis

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Further assumptions

• Agents act *rationally* and *simultaneously* while taking into account the activities of the other agents

• *No* consideration of *sequential moving* and issues of *timing*

• *Perfect competition* on the generation stage

• *Perfect regulation* of the TSOs (aligned with social objectives)

• All agents are *price-taking*; prices are determined by an independent institution through market clearing

• Solution is an inter-temporal equilibrium
  → unique for convex functions ⇔ unique ordering of settings
### Setting I: Nodal pricing

**Two alternative formulations**

<table>
<thead>
<tr>
<th>Integrated</th>
<th>Decomposed</th>
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<tbody>
<tr>
<td><strong>P1</strong> Integrated Problem</td>
<td><strong>P1’a</strong> Generation</td>
</tr>
<tr>
<td>$\min_{\bar{G}, G, T_{i,j}, \bar{P}<em>{i,j}} \quad X = \sum_i \delta_i \bar{G}<em>i + \sum_i \gamma_i G_i + \sum</em>{i,j} \mu</em>{i,j} \bar{P}_{i,j}$</td>
<td>$\min_{\bar{G}, G, T_{i,j}} \quad X = \sum_i \delta_i \bar{G}<em>i + \sum_i \gamma_i G_i + \sum</em>{i,j} \kappa_{i,j} f(T_{i,j})$</td>
</tr>
<tr>
<td>s.t. $G_i - \sum_j T_{i,j} = d_i \quad \forall i \quad \mid \lambda_i$</td>
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<tr>
<td>$</td>
<td>P_{i,j}</td>
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$\rightarrow$ **Equivalent problem!**

- **Integrated** = **Decomposed**, due to perfect exchange of (price) information
- Both formulations represent **first-best design**
### Setting I versus Setting II

#### Nodal pricing

**P1'a  Generation**

\[
\begin{align*}
    \min_{\overline{G}_i, G_i, T_{i,j}} & \quad X = \sum_i \delta_i \overline{G}_i + \sum_i \gamma_i G_i + \sum_{i,j} \kappa_{i,j} f(T_{i,j}) \\
    \text{s.t.} & \quad G_i - \sum_j T_{i,j} = d_i \quad \forall i \quad |\lambda_i| \\
    & \quad G_i \leq \overline{G}_i \quad \forall i
\end{align*}
\]

**P1'b  Transmission**

\[
\begin{align*}
    \min_{\overline{P}_{i,j}} & \quad Y = \sum_{i,j} \mu_{i,j} \overline{P}_{i,j} \\
    \text{s.t.} & \quad |P_{i,j}| = f(T_{i,j}) \leq \overline{P}_{i,j} \quad \forall i, j \quad |\kappa_{i,j}|
\end{align*}
\]

#### Zonal pricing with redispatch

**P2a  Generation**

\[
\begin{align*}
    \min_{\overline{G}_i, G_i, T_{m,n}} & \quad X = \sum_i \delta_i \overline{G}_i + \sum_i \gamma_i G_i + \sum_{m,n} \kappa_{m,n} T_{m,n} \\
    \sum_{i \in I_m} G_i - \sum_{n} T_{m,n} = \sum_{i \in I_m} d_i \quad \forall m \quad |\lambda_m| \\
    & \quad G_i \leq \overline{G}_i \quad \forall i
\end{align*}
\]

**P2b  Transmission**

\[
\begin{align*}
    \min_{\overline{P}_{i,j}, R_i} & \quad Y = \sum_{i,j} \mu_{i,j} \overline{P}_{i,j} + \sum_i \gamma_i R_i \\
    \text{s.t.} & \quad |P_{i,j}| = \overline{f}(G_i, d_i) \leq \overline{P}_{i,j} \quad \forall i, j \quad |\kappa_{i,j}| \\
    & \quad \sum_{i \in I_m} R_i = 0 \quad \forall m \\
    & \quad 0 \leq G_i + R_i \leq \overline{G}_i \quad \forall i \\
    & \quad \kappa_{m,n} = g(\kappa_{i,j})
\end{align*}
\]

- Setting II averages nodal prices to zonal prices → **loss of information**
- Redispatch unable to fully resolve inefficiency
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Large-scale application – CWE region

Model
• EWI-DIMENSION coupled with Energynautics grid model via PTDF

Configuration
• CWE region: 70 nodes, 174 lines
• 2011, 2020 and 2030 analyzed
• 9 type-days (8 normal / 1 extreme)

Numerical solution
• Decomposition into master (gen.) and subproblem(s) (trans.)
→ Consistent implementation of the economic framework
→ Iterative PTDF update (Hagspiel et al. (2014))
Results: Comparison of total system costs

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Conclusions

• Modeling framework for short and long-term effects of various congestion management designs
  – Generalized and consistent analytical formulation
  – Numerically tractable by suggested algorithm
• Nodal pricing is first-best; alternative designs hide information and induce inefficiencies
• Major deteriorative factors for efficiency: non-coordinated TSOs and low trading capacities offered to the market; relative effect rather small
• Findings corroborate ongoing efforts to implement flow-based market coupling (even though not first-best) and closer TSO coordination
• Possible extensions: Strategic behavior (e.g. different regulation regimes); Tradeoff with implementation costs (e.g. public acceptance)
Thank you for your attention! Questions and comments are very welcome.

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Tel.: +49 221 27729-222

Financial support by the “Energy Storage Initiative” through grant 03ESP239 is gratefully acknowledged.
Analytical formulation of Setting III

Coupled zonal markets, zonal TSOs, redispatch

**P3a Generation**

\[
\begin{align*}
\min_{G_i, \hat{G}_i, T_{m,n}} & \quad X = \sum_i \delta_i \hat{G}_i + \sum_i \gamma_i G_i + \sum_{m,n} \kappa_{m,n} T_{m,n} \\
\text{s.t.} & \quad \sum_{i \in I_m} G_i - \sum_n T_{m,n} = \sum_{i \in I_m} d_i \quad \forall m \quad |\lambda_m| \\
& \quad G_i \leq \hat{G}_i \quad \forall i
\end{align*}
\]

**P3b Transmission**

\[
\begin{align*}
\min_{P_{i,j} \in I_m, R_i \in I_m} & \quad Y_m = \sum_{i,j \in I_m} \mu_{i,j} \bar{P}_{i,j} + \sum_{i,j \in I_{m,cb}} \sigma_{i,j} \mu_{i,j} \bar{P}_{i,j} + \sum_{i \in I_m} \gamma_i R_i \quad \forall m \\
\text{s.t.} & \quad |P_{i,j}| = \hat{f}(G_i, d_i) \leq \bar{P}_{i,j} \quad \forall i, j \in I_m \quad |\kappa_{i,j} \in I_m| \\
& \quad \sum_{i \in I_m} R_i = 0 \\
& \quad 0 \leq G_i + R_i \leq \hat{G}_i \quad \forall i \in I_m \\
& \quad \kappa_{m,n} = g(\kappa_{i,j})
\end{align*}
\]
Analytical formulation of Setting IV

Coupled zonal markets, zonal TSOs, g-component

\[ P_{4a} \quad \text{Generation} \]

\[ \min_{\overline{G}_i, G_i, T_{m,n}} X = \sum_i \delta_i \overline{G}_i + \sum_i \gamma_i G_i + \sum_{i,j} \kappa_{i,j} \hat{f}(G_i, d_i) \]

s.t. \[ \sum_{i \in I_m} G_i - \sum_n T_{m,n} = \sum_{i \in I_m} d_i \quad \forall m \quad |\lambda_m| \]
\[ G_i \leq \overline{G}_i \quad \forall i \]

\[ P_{4b} \quad \text{Transmission} \]

\[ \min_{P_{i,j} \in I_m \cdot I_m, cb} Y_m = \sum_{i,j \in I_m} \mu_{i,j} \overline{P}_{i,j} + \sum_{i,j \in I_m, cb} \sigma_{i,j} \mu_{i,j} \overline{P}_{i,j} \quad \forall m \]

s.t. \[ |P_{i,j}| = \hat{f}(G_i, d_i) \leq \overline{P}_{i,j} \quad \forall i, j \in I_m, I_m, cb \quad |\kappa_{i,j} \in I_m, I_m, cb| \]
Convergence and optimality
Results: Aggregated line capacities, AC and DC

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Results: Exemplary grid expansion and regional allocation of renewable energies

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