Network Expansion to Mitigate Market Power
How Increased Integration Fosters Welfare

Daniel Huppmann, Alexander Zerrahn
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Agenda

1. Theory: *Market power in constrained networks*
2. Policy: *The economics of network investment*
3. Math: *A three-stage model for network investment and strategic generators*
4. Example: *A toy model for illustration purposes*
5. Conclusion and outlook
Theory:
Market power in constrained networks
The theoretical background: Strategic behaviour in networks

In constrained networks, strategic generators may choose to congest lines to divide the market and earn monopoly profits

- Bushnell et al. (2000) illustrate this in a simple two-node example

- Cournot generators are able to earn extra rents by congesting the line and barring the other player from exporting to their market
- This is referred to as passive-aggressive equilibrium
- But even in this simple example, existence & uniqueness of an equilibrium depend on the line capacity
Numerical modelling: Capturing strategic behaviour is complicated

Applied/numerical modelling has largely abstracted from these effects due to the mathematical complexity

- Generators are frequently modelled as Cournot players (or using conjectural variations or supply function equilibria)
- But in most applied work, strategic players don’t consider their impact on network congestion and resulting price differentials
- The problem becomes even more difficult when including power flow characteristics in networks
cf. Neuhoff et al. (2005)

⇒ Hence, most numerical applied work underestimates the potential for gaming in (electricity) networks
Policy:

The economics of network investment
The benefits of network expansion

Network expansion can yield substantial benefits by improving efficiency and mitigating market power potential

- In a perfectly competitive market, you would invest up to the point where \( \text{marginal cost of investment} = \text{marginal benefits} \) (efficiency)
- But when generators are aware of their impact on grid congestion, this is quite difficult to compute
- It can be optimal to invest in a line which is not used in equilibrium
- This happens because the passive-aggressive equilibrium is no longer stable and generators revert to the Cournot equilibrium

\[ \implies \text{With strategic generators present, network investment can yield benefits beyond efficiency gains by mitigating market power} \]
The ugly math:

A *three-stage model for network investment and strategic generators*
Modelling a strategic generator taking into account its impact on nodal prices is mathematically challenging

This yields a Mathemtical Program under Equilibrium Constraints (MPEC, e.g., Gabriel and Leuthold, 2010; Ruiz and Conejo, 2009)
Finding an equilibrium between strategic generators is even more challenging

- This yields an Equilibrium Problem under Equilibrium Constraints (EPEC, e.g., Ruiz, Conejo and Smeers, 2012; Pozo et al., 2013)
A network planner decides on investment, balancing costs against efficiency gains and market power mitigation.

1. **Network planner**
   - Seeks to maximize aggregate welfare
   - Decides on grid upgrades

2. **Strategic generator**
   - Each strategic generator faces a bilinear optimization problem under equilibrium constraints
   - Take KKT conditions and reformulate using disjunctive constraints

3. **Electricity market (ISO)**
   - Welfare maximization of spot market reformulated using strong duality

⇒ The resulting problem is a non-convex (bilinear) Mixed-Integer Quadratically Constrained Quadratic Program.
A numerical example:

A *toy model for illustration purposes*
A simple case study:

- A three node network
- Demand at $n1$, inverse demand function: $p(q) = 10 - q$
- Generation at $n2$ and $n3$
- Marginal generation cost 0
- Initial line capacity as indicated

\[
\begin{align*}
\bar{f}_1 &= 0.5 \\
\bar{f}_2 &= 1 \\
\bar{f}_3 &= 3
\end{align*}
\]
A numerical application – Market power cases

Potential Nash equilibria: benchmark & after expansion

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<tr>
<td>Generation</td>
<td>1.90</td>
<td>0.55</td>
<td>1.75</td>
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<td>Price at $n1$</td>
<td>7.55</td>
<td>5.75</td>
<td>3.33</td>
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The *thin-line* effect (cf. Borenstein et al., 2000):
Line upgrades may be necessary to make Nash equilibria stable against deviations, even if these lines are not utilized in equilibrium.
A numerical application – Market power cases

Potential Nash equilibria: welfare effects

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Diagram showing potential Nash equilibria with welfare, investment costs, firm 2 profit, firm 3 profit, and consumer surplus.
Proactive vs. reactive network investment

- Assume that a benevolent network planner invests as if all generators would act competitively, when in fact they behave strategically (*reactive* investment) (cf. Sauma and Oren, 2006)
- Solve for Nash equilibrium with “competitive” grid investment: In our test case: there exists no Nash equilibrium!

A philosophical question:

What is the interpretation of “no Nash equilibrium”...?
Conclusion and outlook
Conclusions and outlook

Theory and methodology:

- We develop a methodology to identify equilibria between strategic generators accounting for their effect on the network
- A network planner balances expansion costs against efficiency gains and market power effects
- There is a lot of ugly math & iterative algorithms to make this work

Policy:

- Network expansion can greatly mitigate market power potential
- Only focusing on congested lines can lead to sub-optimal decisions
- Failing to anticipate strategic behaviour can lead to funny effects
Thank you very much for your attention!