Decision making in electricity markets: Bi-level games and stochastic programming

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Two decision problems of power producers:

I. Strategic: Investment & production decision
   - Bi-level game with several producers
   - Numerical solutions

II. Operational: Dispatch of pumped-storage hydropower
   - Stochastic programming problem
   - Exact solution
Scope of the bi-level game model

- Aim for the policy maker: Anticipate investment, production and trading decisions of producers in the European electricity market, and especially for Switzerland
- Focus on producers (and not consumers)
- Oligopolistic market (producers can influence prices):
  - Producers can withhold production, or limit investment to drive prices up
  - Producers can invest more what is demanded to deter market entry of other players
  - Market power may be exerted only in some sub-markets (e.g. during peak-hours)
- Complements PSI’s energy-system cost-optimization models
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Is there market power?

“Yes”: EEX market, Jan+Feb 2006, especially at peak-load (Willems, Rumiantesva & Weigt, 2009)


“Less over time”: Spanish market (Moutinho, 2014) Dutch market (Mulder, 2015)

- Regulations (transparency measures) may mitigate short-term market power
- Investments (e.g. solar in Germany, nuclear in France) are still facilitated on country-level
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→ Assumption (first project phase): Players are countries (CH, DE, AT, IT, FR)
Multi-leader–follower game (Murphy & Smeers, 2005):

1st Stage (investment decision):
- Optimization of Player 1: Investment in supply technologies
- Optimization of Player 2: Investment in supply technologies
- Optimization of Player 3

2nd Stage (day-ahead market):
- Quantity Bidding (peak/base)
- Market clearing of TSO (price-taker) under transmission constraints

i.e., producers first invest (lock-in), then they play Nash-Cournot production game together

1st project phase with 5 players: CH, DE, AT, FR, and IT.
Mean-risk bi-level optimization for each player (producer)

For each player $i$:

$$\max \text{ expected total profit} = \left( \text{profit from selling power} - \text{capital costs} \right) \text{ summed over load-periods and scenarios}$$

s.t.

- capacity $\leq$ max-capacity, for each technology, e.g. maximum potential for player $i$
- constraint on risk, on total profit
- production-, import-amounts, and prices are given by:

$$\max \text{ total profit of player } i'$$

s.t.

- $\text{production}_{i'} \leq \text{capacity}_{i'}$, for each technology, load period, and scenario

$$\text{price}_{i'} = f_{i'}(\text{production}_{i'} + \text{import}_{i'})$$

for each load period, and scenario

Currently implemented:

- Financial constraint on risk is relaxed
- Stochastics: 16 demand scenarios (level and elasticity variation)
Optimization for each player $i$ (producer)

- $i \in I$: player, $l \in L$: load period, $\xi \in \Xi$: scenario, $|\Xi| < \infty$
- Variables: $x_i \in \mathbb{R}^n_+$: investment in $n$ different technologies, $y_{il\xi} \in \mathbb{R}$: total profit, $q_{il\xi} \in \mathbb{R}_+^n$: production, $a_{il\xi} \in \mathbb{R}$: import, $p_{il\xi} \in \mathbb{R}$: price
- $\delta_l$: length load period, $x_i^0/x_i^{\text{max}}$: initial/maximal capacity, $\beta_i$: capital costs
- Inverse linear demand function: $p_{0il\xi}, b_{il\xi}$: intercept and slope
- Risk measure Average-Value-at-Risk AVaR at level $\alpha$ and lower bound $\rho_i$; $\mathbb{E}[\cdot]$: expected value over the scenarios; $e := (1, \ldots, 1)^T \in \mathbb{R}^n$

$$\begin{align*}
\max_{x_i} & \sum_{l \in L} \delta_l \mathbb{E}[y_{il\xi}] \\
\text{s.t.} & \begin{cases}
y_{il\xi} = q_{il\xi}^\top (p_{il\xi} e - c_i) - \beta_i^T x_i, \\
x_i^0 + x_i \leq x_i^{\text{max}}, \\
\text{AVaR}_\alpha \left[ \sum_{l \in L} \delta_l y_{il\xi} \right] \geq \rho_i,
\end{cases}
\end{align*}$$

market power: $p_{il\xi}^\prime(q_{il\xi}) = b_{il\xi}$

$$\begin{align*}
q_{il\xi}, a_{il\xi}, p_{il\xi} & \in \arg \max_{q_{i'l\xi}, a_{i'l\xi}} y_{i'l\xi} \\
\text{s.t.} & \begin{cases}
q_{i'l\xi} \leq x_{i'}^0 + x_{i'}, \\
p_{i'l\xi} = p_{i'l\xi}^0 + b_{i'l\xi} (q_{i'l\xi}^\top e + a_{i'l\xi}), \quad \forall i', l, \xi.
\end{cases}
\end{align*}$$
Assumptions: Price-demand, costs

- Price is linear in demand (data EPEX/GME; 2015, 0h+12h)
- All demand is traded (today: DE/AT 45%, CH 35%, FR 20%)
- New capacity has same costs as existing

Solar/wind with average availability

Cost data and maximal capacity-expansion: EU-JRC model
Simple transmission model between countries

- DC flow model (lines have same reactances)
- Aggregated transmission capacity between countries
- No fringe region; no endogenous transmission expansion
- TSO (price-taker) maximizes profit of redistributing electricity; producers are paid locational price

Players may base investment decisions on such simplifications
Solution method: Players’ + TSO’s optimizations

In steps 1.→2.→3. because of non-convexities:

1. Social Welfare (SW) maximization problem
   • Convex quadratic problem (CPLEX solver)

2. Simplified problem: Investment & production decided together
   • Start with solution from 1.
   • Linear mixed-complementarity problem (PATH solver)

3. Bi-level problem formulated as EPEC (Equilibrium problem with equilibrium constraints)
   • Start with solution from 2.
   • Solve MPEC (Mathematical program with equilibrium constraints) for each player (MPEC solver of GAMS)
   • Diagonalization over the players (Hu & Ralph, 2007): Each MPEC is solved with first-stage decision of other players fixed. STOP: numerical convergence in 1st stage decisions
Preliminary result: Influence of market power

Assumptions:

- Same price-elasticity scenarios for players
- Existing capacity scaled down to 50% (because of today’s overcapacity in Europe)

FR cannot exert market power; if DE/IT has market-power, CH exports
Preliminary result: Influence of transmission constraints

- **Investments**: SW > price-taker > market-power
- **Removable of transmission constraints**:
  - Case SW: Production where cheapest (DE lignite)
  - Case market-power: More trade, but not higher profits
II: Operational decisions of producers

- Usually much more focused: Exogenous electricity prices, single player etc.
- Easier problem formulations possible? For example: Is there a simple dispatch problem with an analytical solution?
Single-period (steady-state) pumped-storage

- $S$: electricity spot price (EUR/MWh), random variable
- $U^\pm$: control function of turbined/pumped water (MWh)
- $c \in (0, 1)$: efficiency of pumping
- Capacity, usable expected water in reservoir: $u_{\text{max}}^+ > l > 0$
- Constraint on water-level is in expectation, and a lower reservoir is neglected

$$\max_{u^\pm} \mathbb{E} \left[ SU^+ - \frac{1}{c} SU^- \right]$$

s.t. $\begin{cases} \mathbb{E} [U^+ - U^-] \geq l, \\
0 \leq U^\pm \leq u_{\text{max}}^\pm. \end{cases}$

Optimal solution:

$$U^+ = u_{\text{max}}^+ 1_{\{S \geq q\}}, \quad U^- = u_{\text{max}}^- 1_{\{S \leq cq\}},$$

$q$ given by: $u_{\text{max}}^+ \mathbb{P}[S \geq q] - u_{\text{max}}^- \mathbb{P}[S \leq cq] = l$
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Conclusions

I. Game-theoretic investment & market model

- Solution procedures (MPEC solver of GAMS; diagonalization over the players) yields economically reasonable local solutions
- Preliminary results: Player ‘Switzerland’ profits
  - from market power of other players,
  - not much from a removal of transmission constraints
- More careful evaluation of assumptions and of data needed

II. Exact solutions of simple problems

- May serve as building blocks in large-scale models
- Help to understand the basic mechanisms

Collaboration is very welcome!
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