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

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Outline

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

- Project for Swiss Federal Office of Energy (2015–2017)
- 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)

"No": EEX market, 2007–2010, peak- and base-load (Graf & Wozabal, 2013)

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

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- Investments (e.g. solar in Germany, nuclear in France) are still facilitated on country-level

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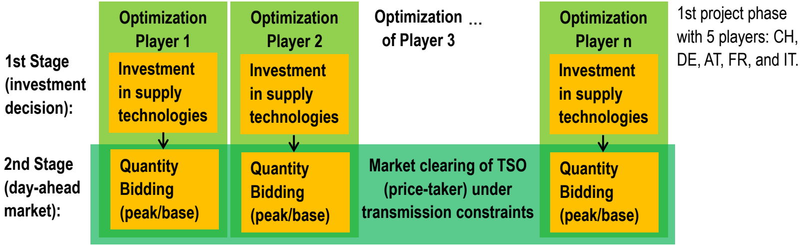
→ Assumption (first project phase): Players are countries (CH, DE, AT, IT, FR)

Game of investment and of subsequent production

Multi-leader–follower game (Murphy & Smeers, 2005):



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

Mean-risk bi-level optimization for each player (producer)

For each player i:

max expected total profit =

$\Big($profit from selling power − capital costs$\Big)$ summed over load-periods and scenarios

s.t.

- capacity ≤ 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 total profit of player i' — for each load period, scenario, and 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)

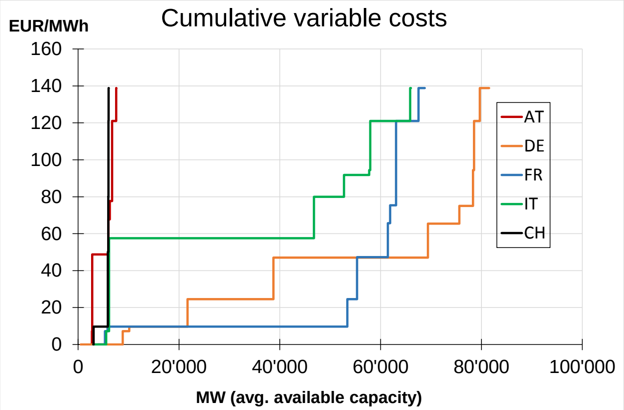
- $i \in \mathcal{I}$: player, $l \in \mathcal{L}$: load period, $\xi \in \Xi$: scenario, $|\Xi| < \infty$
- Variables: $x_i \in \mathbb{R}^n_+$: investment in n different technologies, $y_{il\xi} \in \mathbb{R}$: total profit, $q_{il\xi} \in \mathbb{R}^n_+$: production, $a_{il\xi} \in \mathbb{R}$: import,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

$$\max_{x_i} \sum_{l \in \mathcal{L}} \delta_l \mathbb{E}\left[y_{il\xi}\right]$$

$$\text{s.t.} \begin{cases} y_{il\xi} = q_{il\xi}^\top \left(p_{il\xi} e - c_i\right) - \beta_i^\top x_i, & e{:=}(1\ldots,1)^\top{\in}\mathbb{R}^n \\ x_i^0 + x_i \le x_i^{\max}, & \text{market power: } p'_{il\xi}(q_{il\xi}){=}b_{il\xi} \\ \mathrm{AVaR}_\alpha\left[\sum_{l\in\mathcal{L}} \delta_l y_{il\xi}\right] \ge \rho_i, & \\ q_{il\xi}, a_{il\xi}, p_{il\xi} \in \operatorname*{arg\,max}_{q_{i'l\xi}, a_{i'l\xi}} y_{i'l\xi} & \\ \qquad \text{s.t.} \begin{cases} q_{i'l\xi} \le x^0_{i'} + x_{i'}, \\ p_{i'l\xi} = p^0_{i'l\xi} + b_{i'l\xi}\left(q_{i'l\xi}^\top e + a_{i'l\xi}\right), \quad \forall i', l, \xi. \end{cases} & \end{cases}$$

Assumptions: Price-demand, costs

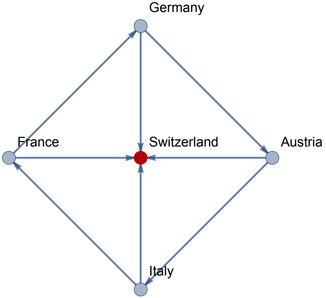
- Price is linear in demand (data EPEX/GME; 2015, 0h+12h)
- All demand is traded (today: DE/AT 45%, CH 35%, FR 20%)
- New capacity has same costs as existing



- 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
  - Metzler, Hobbs & Pang (2003): (Producers sell to TSO at locational prices) ⇔ (Bilateral trading & TSO/arbitrageur is price-taker).

Players may base investment decisions on such simplifications

Solution method: Players' + TSO's optimizations

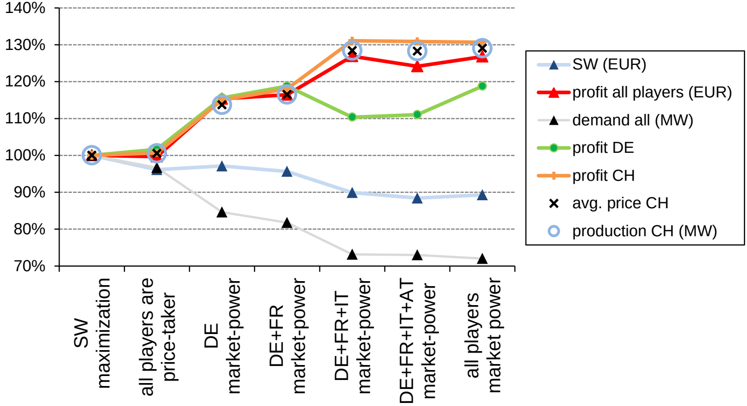
In steps 1.→2.→3. because of non-convexities:

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

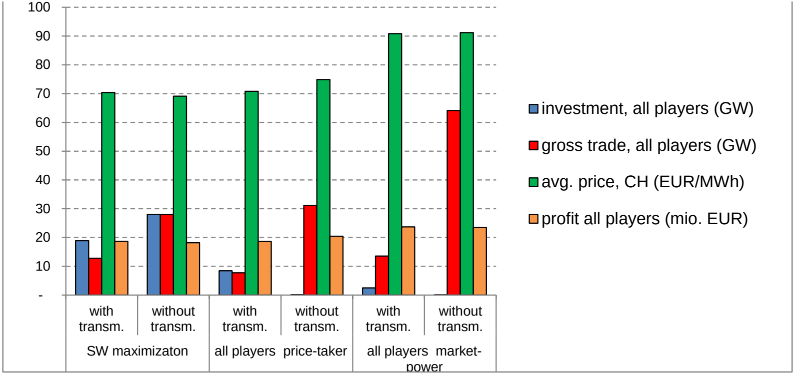
Assumptions:

- 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: $u^{+}_{\max} > I > 0$
- Constraint on water-level is in expectation, and a lower reservoir is neglected

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

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

Optimal solution:

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

q given by: $u^{+}_{\max}\mathbb{P}[S \geq q] - u^{-}_{\max}\mathbb{P}[S \leq cq] = I$

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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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