Modeling of Electricity Markets and Hydropower Dispatch
Task 4.2: Global observatory of electricity resources

Martin Densing, Evangelos Panos
Energy Economics Group, PSI
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Task 4.2 for Energy Economics Group at PSI

• Topic: Future market options of Swiss electricity supply
  – Interaction of Swiss electricity system with EU electricity supply
  – Scenarios under which the Swiss electricity system, especially hydropower, can be profitable

• Tools: Economic electricity models
  – Social-planner optimization (perfect competition model): Electricity system model “EU-STEM” → Poster
  – Electricity markets: Nash-Cournot equilibrium model “BEM” → Poster
  – Dispatch of hydropower under uncertainty

1. Analytical modeling
   • Numerical modeling (Mean-risk models using multistage-stochastic programming)

EU-STEM: European Swiss TIMES electricity model
BEM: Bi-level electricity market model
Modeling of electricity market prices

• Why? Flexible stored hydro power can profit from electricity price peaks (pumped-hydro also from spreads)
• How to model the price peaks, i.e., price volatility?
  – Econometric time series estimation, e.g. with a fundamental model: Electricity price ~ Gas price + Demand + CO2 price + etc.
    • usually no detail on generation technology
  – Technology-detailed model of supply cost curve
    • data intensive (e.g. all plants with outages), commercial software exists, usually perfect-competition assumption with a mark-up
• Design principle of BEM model: Balancing modeled details of technologies and markets. Relevant for SCCER-SoE:
  – Price volatility should be captured
  – Technologies should be represented
Bi-level Electricity-Market model (BEM)

- General framework to understand price-formation and investments
- Investment and subsequent production decision of several power producers
- Producers can influence prices by withholding investment or production capacity in certain load periods

1

2

\[ \text{Optimization Player 1} \]
\[ \text{Optimization Player 2} \]
\[ \text{Optimization Player 3...} \]
\[ \text{Optimization Player N} \]

- Investment in supply technologies
- Investment in supply technologies
- Investment in supply technologies
- Investment in supply technologies

\[ \text{Quantity bidding (4*24hours)} \]
\[ \text{Quantity bidding (4*24hours)} \]
\[ \text{Market clearing of TSO under transmission constraints (price-taker)} \]
\[ \text{Quantity bidding (4*24hours)} \]

- Bi-level Nash-Cournot game; Multi-leader multi-follower-game, EPEC
- BEM can run in different modes: (i) Investment and production decision on same level (ii) Single scenario (deterministic) (iii) Social welfare maximization
Modeling competitive behavior (market power)

- Transparency measures now imposed by regulators reduce possibility of market power on wholesale power markets
  - Market power := Deliberate back-holding of generation capacity, yielding a price higher than marginal cost of merit-order [Cournot, 1838]
- Assumption in BEM: Price effects of market power and of other scarcity effects are indistinguishable
  - E.g.: Temporary nuclear shut-down → Effect as “as-if” market power

BEM model (Estimation mode):

• **Input**: Hourly historical prices, market volumes, generation (for each country)
  → Calibration of «as-if» market power parameter (for each country and representative load period)

BEM model (Normal mode):

• **Output**: prices, volumes, generation by technology
Bi-level Electricity-Market model (BEM)

- Transmission constraints between players (linear DC flow model)
- Wholesale consumers represented by demand-price elasticity. Two markets in each node: (i) Spot-market, (ii) Demand cleared OTC (inelastic)
- Hourly trading: A typical day in the future for 4 season (4*24 load periods)
- **Base configuration:** Players are countries
- Input: CAPEX, OPEX of technologies, seasonal availabilities etc.
Model validation: Competitiveness & thermal plant constraints

Volatility of hourly price: (example: Winter)

<table>
<thead>
<tr>
<th></th>
<th>DE</th>
<th>CH</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 (EPEX)</td>
<td>54%</td>
<td>25%</td>
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<tr>
<td>Social welfare</td>
<td></td>
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<tr>
<td>maximization</td>
<td></td>
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<tr>
<td>(without thermal</td>
<td></td>
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<tr>
<td>constraints)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social welfare</td>
<td>0%</td>
<td>2%</td>
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<tr>
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<td></td>
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<tr>
<td>Competitive model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(without thermal</td>
<td>13%</td>
<td>10%</td>
</tr>
<tr>
<td>constraints)</td>
<td></td>
<td></td>
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<tr>
<td>Competitive model</td>
<td>25%</td>
<td>26%</td>
</tr>
<tr>
<td>DE-WI Scenario with</td>
<td>35%</td>
<td>33%</td>
</tr>
<tr>
<td>average wind &amp; solar</td>
<td></td>
<td></td>
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<tr>
<td>generation</td>
<td></td>
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</tr>
</tbody>
</table>

Price (Germany, winter)

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Model validation: Switzerland

Price (Switzerland, summer)

- Social welfare, no dispatch constraints
- Social welfare, dispatch constraints
- Competitive market, no dispatch constraints
- Competitive market, dispatch constraints
- Seasonal avg. price EPEX 2016 (+/-SD)
Model validation: Switzerland

Price (Switzerland, summer)

- social welfare, no dispatch constraints
- social welfare, dispatch constraints
- competitive market, no dispatch constraints
- competitive market, dispatch constraints
- seasonal avg. price EPEX 2016 (+/-SD)

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Test: Immediate nuclear switch-off in Switzerland?

Result:
- No new investments (enough existing capacity in neighboring countries)
- CH imports more: 0.4 GW/h (avg.) → 3 GW/h
- Social Welfare (overall all countries, markets): −10%
- Producer’s profit: CH: −9%; avg. other countries: +22%

![Nuclear Switch-off in Switzerland - Price increase, per season](image)
Secondary ancillary service

- Secondary reserve power: Fully available after 15min.
- Approx. +/- 400 MW in Switzerland in 2016 (causes: wind + solar, demand, hourly step schedule in Europe)

Ancillary service reduces the flexibility of operation: What is tradeoff between locked-in and free production?
Secondary ancillary service: Contract details

- Producer having capacity $u_{\text{max}}$ provides power $\pm u_a$ (MW) over a week; producer sells $u_{\text{min}} + u_a$ at the market.

- Payment for capacity: TSO pays producers (pay-as-bid auction)
- Payment for energy:
  - TSO pays producer for up-regulation energy (at 120% market price)
  - Producer pays TSO for down-regulation energy (at 80% market price)
  - $\approx 1.6 \text{ Rp./MWh (in 2016)} < \text{ capacity payment}$
Stochastic model of secondary service

Condition to go into ancillary service:
Capacity payment > Mean absolute deviation from median of spot price (MAD), a measure of price volatility

Use of residual free capacity for market:
Bang-Bang control (either turbine at full or at zero capacity)

Energy payment neglected

Profit maximization problem:

\[
\max_{u(\cdot), u_a} \mathbb{E} [S(u(S) + u_a)] + p_a u_a \quad \text{s. t.}
\]

\[
\mathbb{E}[u(S) - u_a] \geq l, \\
u(S) + 2u_a \leq u_{\text{max}}^+, \\
u(S), u_a \geq 0,
\]

Explicit solution:

\[
\hat{U} = \hat{u}(S) = (u_{\text{max}}^+ - 2\hat{u}_a) 1\{S \geq \hat{q}\}
\]

\[
\hat{u}_a = \left( \frac{1}{2} u_{\text{max}}^+ - \frac{l - \frac{1}{2} u_{\text{max}}^+}{1 - 2\mathbb{P}[S \leq \hat{q}]} \right) 1\{p_a > \mathbb{E} [|S - m|]\}
\]

1_{\{S \geq q\}}: Indicator function: If spot price S is higher or equal than q, then 1, else 0. Hence, if 1, then free production is possible.

q: Marginal value of the water constraint
m: Median of electricity spot price distribution
E[|S - m|]: Mean absolute deviation of spot price distribution
P[S \leq q]: Probability that spot price S is lower or equal q

S: Spot electricity price, random variable (EUR/MW)
u(S): Free dispatch as function of electricity price S
u_a: Set-point of ancillary service, agreed with TSO (MW)
p_a: Total payments for providing ancillary service (EUR/MW)
l: Usable water (= water level + inflow in expectation) (MWh)
u_{\text{max}}^+: Turbine capacity (MW)
E[\cdot]: Expectation (= average over all electricity price scenarios)
Auction results: Ancillary service

Volume-avg. SDL price, weekly, 2016/2017

MAD := Mean Absolute Deviation from Median
SDL profitable $>_{(strictly)}$ MAD of spot price

Figure 3: Ancillary service $u_a$ as a function of the reimbursement $p_a$. Parameters: $u_{\text{max}}^+ = 1; l = 0.8; \text{random variable } S \sim N(10, \sigma = 2.5)$
Outlook of economic modeling in Phase II

• Further development of BEM model
  – BFE-EWG project: Policy scenarios (jointly with University of Zurich)
  – VSE-PSEL project: Price scenarios
  – Data harmonization: University of Basel, SCCER Joint Activity on Scenarios & Modeling

• Stochastic hydropower modeling
  – BFE-EWG project: Capacity markets etc. (jointly with Karlsruhe Institute of Technology)
BACKUP SLIDES:
Model validation: Competitiveness & thermal plant constraints

Price (CH, WI)

- social welfare, no dispatch constraints
- social welfare, dispatch constraints
- competitive, no dispatch constraints
- competitive, dispatch constraints
- avg. price EPEX

Model validation: Competitiveness & thermal plant constraints
Model validation: Competitiveness & thermal plant constraints

![Price (CH, WI)](image)

- Social welfare, no dispatch constraints
- Social welfare, dispatch constraints
- Competitive, no dispatch constraints
- Competitive, dispatch constraints
- Avg. price EPEX

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Bi-level modeling: Influence of market power

**Example:** Players are whole countries (i.e., production portfolio):

- Switzerland (CH) and neighboring countries (DE, FR, IT, AT)

→ Test influence of country’s market power on spot-market prices and volumes

- FR cannot exert market-power because of flat (nuclear) merit-order curve
- DE and IT have market-power because of non-flat merit-order curve (e.g. gas in IT)
- CH exports more
Impact of dispatch constraints of thermal generation

Results from Social Welfare maximization, Base scenario
Exact Solutions of Hydropower Dispatch

- Pumped-storage optimal-dispatch should consider: Stochastic spot prices & water inflow
- Usual approach is to use large-scale numerical optimization models
- Alternative: Simplified models with analytical solutions → insight in optimal dispatch
- Feature-sets possible: (i) Expected profit maximization (over price scenarios), (ii) expected constraints on water level, (iii) several reservoirs & time-steps, (iv) ancillary service

Optimal dispatch is a “bang-bang” control (using optimal control theory [LaSalle 1959]):

Ancillary service (“Systemdienstleistung”):

Storage-plant operator must decide:
- Either: Sell energy freely on spot market
- Or: Sell production capacity as ancillary service to TSO (i.e. operator loses freedom)

The condition is (with some simplifications):

\[ p \geq \mathbb{E}[|S - m|] \]

Hence: If volatility is high, then go to spot market

→ for details, see poster

M. Densing (2014): Pumped-storage hydropower optm.: Effects of several reservoirs and of ancillary services, IFORS 2014
M. Densing, T. Kober (2016): Hydropower dispatch: Auxiliary services, several reservoirs and continuous time (preprint)
Solar and Wind

<table>
<thead>
<tr>
<th></th>
<th>solar</th>
<th>wind</th>
<th>demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>solar</td>
<td>1</td>
<td>−0.13</td>
<td>0.45</td>
</tr>
<tr>
<td>wind</td>
<td>−0.13</td>
<td>1</td>
<td>0.088</td>
</tr>
<tr>
<td>demand</td>
<td>0.45</td>
<td>0.088</td>
<td>1</td>
</tr>
</tbody>
</table>

2012–2014, all seasons

Hourly average per season and per year:

Solar

Wind
Wind+Solar Scenario Generation

PCA of the multivariate random vector of hourly solar and wind availability (dimension: 48 = 24 + 24). Example data: DE, spring (Mar+Apr+May), 2012–2014:

Variance of Principal Components

85% (92%) of variance by principal component 1.+2.(+3.)
Wind+Solar Scenarios using 1st and 2nd PCA factors with PCA:

\[ X = \Lambda F + \varepsilon, \quad \Lambda^T \Lambda = 1, \quad F \approx \Lambda^T X, \] with random vectors \( X, \varepsilon \in \mathbb{R}^p, F \in \mathbb{R}^k, k < p = 48; F \) not correlated.

\[ 8 \cdot 8 = 64 \] scenarios of \((k = 2)\) first factors in \( F \)

- Factors assumed to be normally distributed \( \rightarrow \) discretization by binomial distribution
- Raw data gives best results (i.e. w/o log \( X \), \( X - \text{mean} X \)) \( \rightarrow \) scenarios with negative values must be ignored
Model Input (i)
Game Theory: Prisoner’s dilemma

• Example of non-cooperative game:
  – \((x, y)\) denotes reward \(x\) of player 1 and reward \(y\) of player 2 under a certain decision of the players

• **Def. Nash Equilibrium:**
  A player cannot improve given the decisions of all other players are fixed

<table>
<thead>
<tr>
<th>Player 1</th>
<th>Player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>invest</strong></td>
<td><strong>do nothing</strong></td>
</tr>
<tr>
<td>(3, 3)</td>
<td>(1, 4)</td>
</tr>
<tr>
<td>(4, 1)</td>
<td><strong>(2, 2)</strong></td>
</tr>
</tbody>
</table>

• The decision leading to \((2, 2)\) is a Nash equilibrium.
Exact Solutions of Hydropower Dispatch

- **Pumped-storage optimal-dispatch** should consider: Stochastic spot prices & water inflow
- Usual approach is to use large-scale numerical optimization models
- **Alternative:** Simplified models with analytical solutions \(\rightarrow\) insight in optimal dispatch
- Feature-sets possible: (i) Expected profit maximization (over price scenarios), (ii) expected constraints on water level, (iii) several reservoirs & time-steps, (iv) ancillary service

**Ancillary service ("Systemdienstleistung"):**

Storage-plant operator must decide:
- Either: Sell energy freely on spot market
- Or: Sell production capacity as ancillary service to TSO (i.e. operator loses freedom)

The condition is (with some simplifications):
\[ p \geq \mathbb{E}[|S - m|] \]
- \(p\): reimbursement from TSO for ancillary service
- \(S\): Spot price
- \(m\): median of spot price

Hence: If volatility is high, then go to spot market
\(\rightarrow\) for details, see poster

**Optimal dispatch is a “bang-bang” control**
(Using optimal control theory [LaSalle 1959]):

**Absolute mean deviation of spot price**
("Volatility" of electricity market price)

\[ \text{Volatility} = \text{Absolute mean deviation of spot price} \]

**Optimal control theory**
[LaSalle 1959]

**Pumping/Production**

\[ \begin{align*}
&\begin{array}{c}
\text{Pumping/Production} \\
\text{100%} \\
\end{array}
\end{align*} \]

\[ \begin{align*}
&\begin{array}{c}
\text{EUR/MWh} \\
\text{22.68} \\
\text{36.85} \\
\end{array}
\end{align*} \]

**References**

M. Densing (2014): Pumped-storage hydropower optim.: Effects of several reservoirs and of ancillary services, IFORS 2014
M. Densing, T. Kober (2016): Hydropower dispatch: Auxiliary services, several reservoirs and continuous time (preprint)
Meta-Analysis (Example: Supply Mix 2050)

Goals of meta-analysis of a scenarios over heterogeneous studies

1. Selection of representative scenarios, which can be used for:
   • Simplified view for policy makers
   • Input to other models that require low-dimensional data (e.g. large economic-wide models with many other data inputs, to keep model sizes small, or stochastic scenario generation)

2. Removal of “superfluous” scenarios: “Is a scenario(-result) “inside” other scenarios?”

3. Quantify extremality of a scenario result “Does a new scenario add variety?”

Meta-Analysis with a Distance Measure

Distance of a scenario to the other scenarios

Example for a supply mix of only 2 technologies:

- \( d_1 \) = Distance of scenario \( x_1 \) to convex hull of all other scenarios
- Scenario \( x_6 \) can be represented as a convex combination of other scenarios \( (d_6 = 0) \)

Minimal set of representative Scenarios:
- BFE WWB + C: business-as usual scenario with new gas plants
- BFE POM + E: renewable scenario with relatively low demand
- PSI-elc, WWB + Nuc: scenario with new nuclear plants and relatively low demand

\( \rightarrow \) The three representative scenarios can be interpreted as major, opposite directions of energy policies in Switzerland.