SCCER SoE

SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

Modeling of Electricity Markets and Hydropower Dispatch

Task 4.2: Global observatory of electricity resources

In cooperation with the CTI

Energy funding programme
Swiss Competence Centers for Energy Research

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

Martin Densing, Evangelos Panos
Energy Economics Group, PSI
14.9.2017

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
  - 1. Electricity markets: Nash-Cournot equilibrium model “BEM” → Poster
  - Dispatch of hydropower under uncertainty
    - 2. Analytical modeling
    - Numerical modeling (Mean-risk models using multistage-stochastic programming)

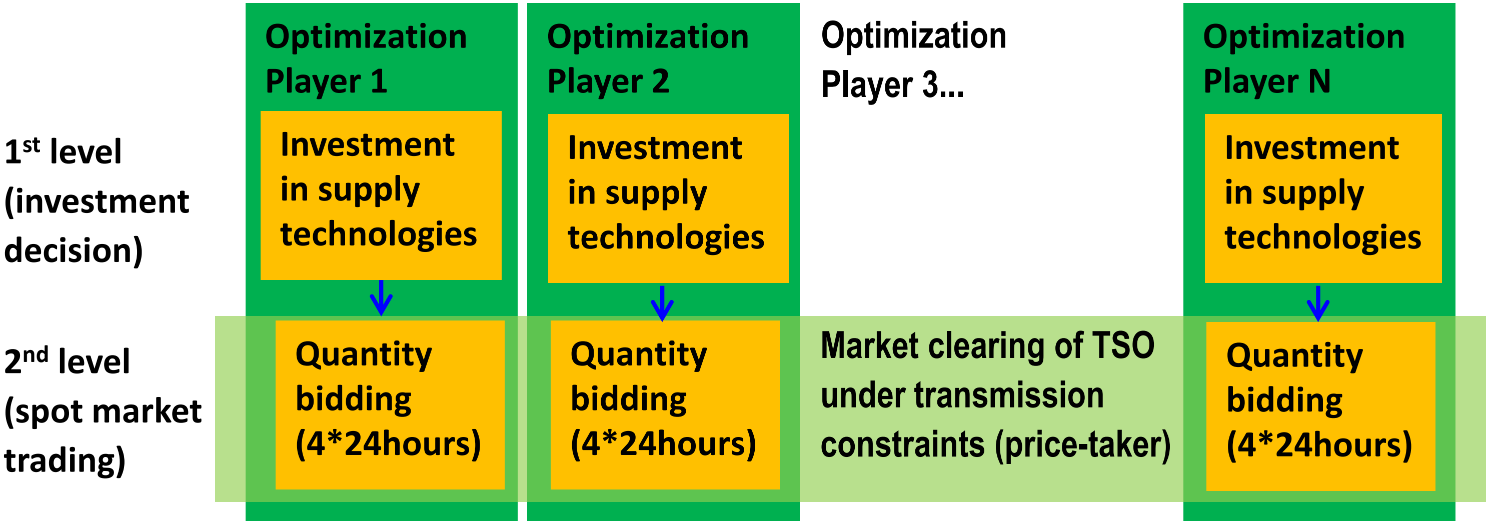
EU-STEM: European Swiss TIMES electricity model
BEM: Bi-level electricity market model

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

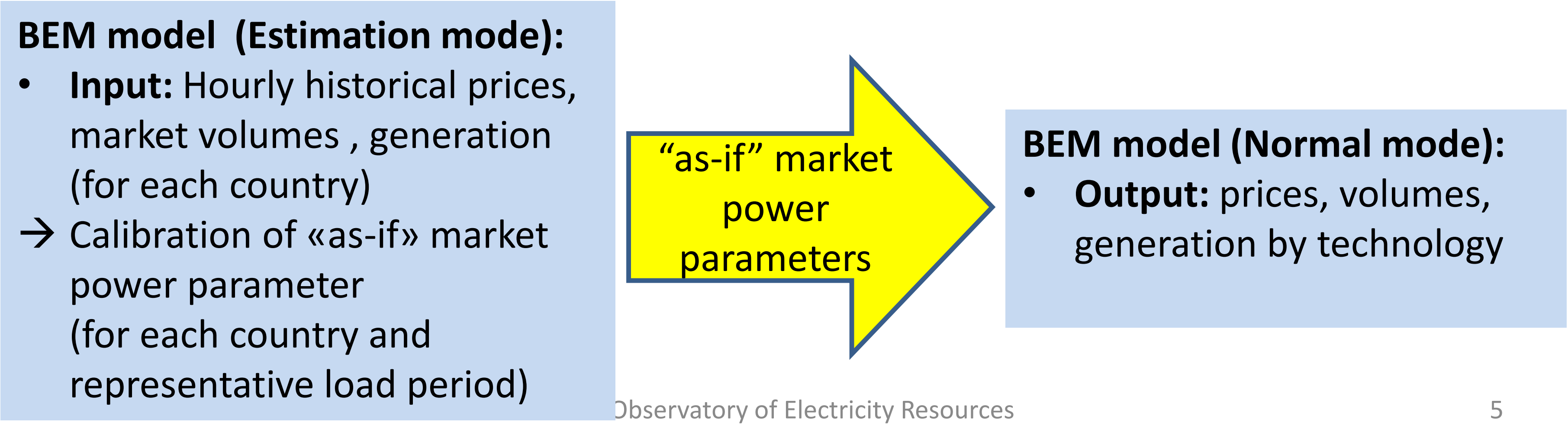


- Bi-level Nash-Cournot game; Multi-leader multi-follower-game, EPEC
- BEM can run in different modes: (i) Investment and production decision on same level (ii) Single scenario (deterministic) (iii) Social welfare maximization

Densing, M., Panos, E., Schmedders, K. (2016): Workshop on Energy Modeling, Energy Science Center, ETHZ

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)

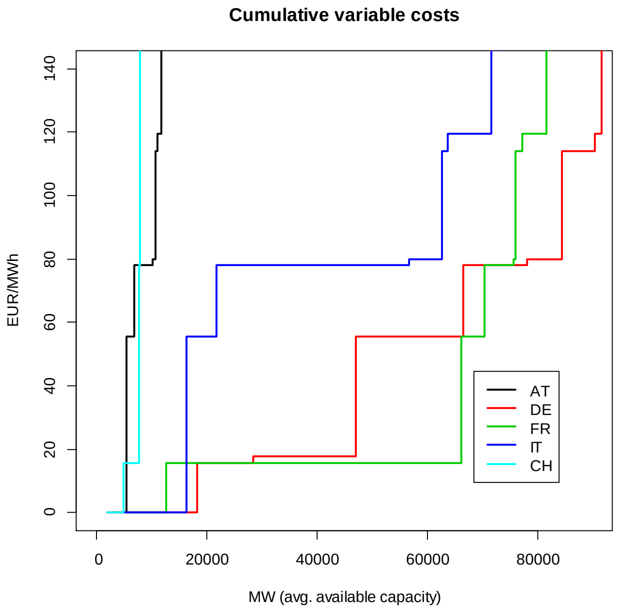
“as-if” market power parameters

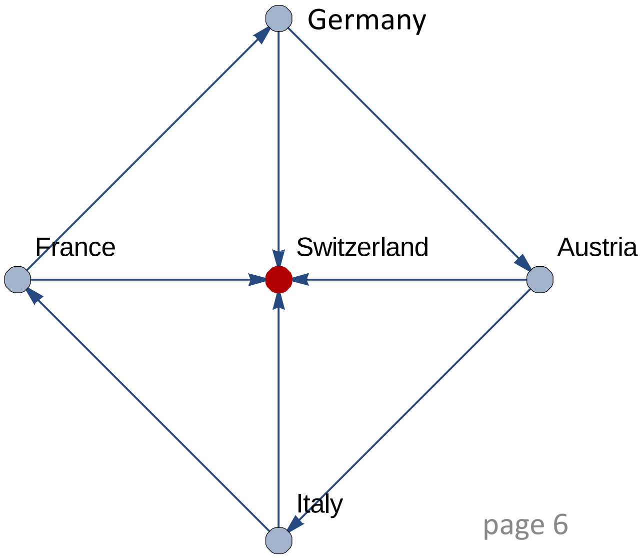
BEM model (Normal mode):

- **Output:** prices, volumes, generation by technology

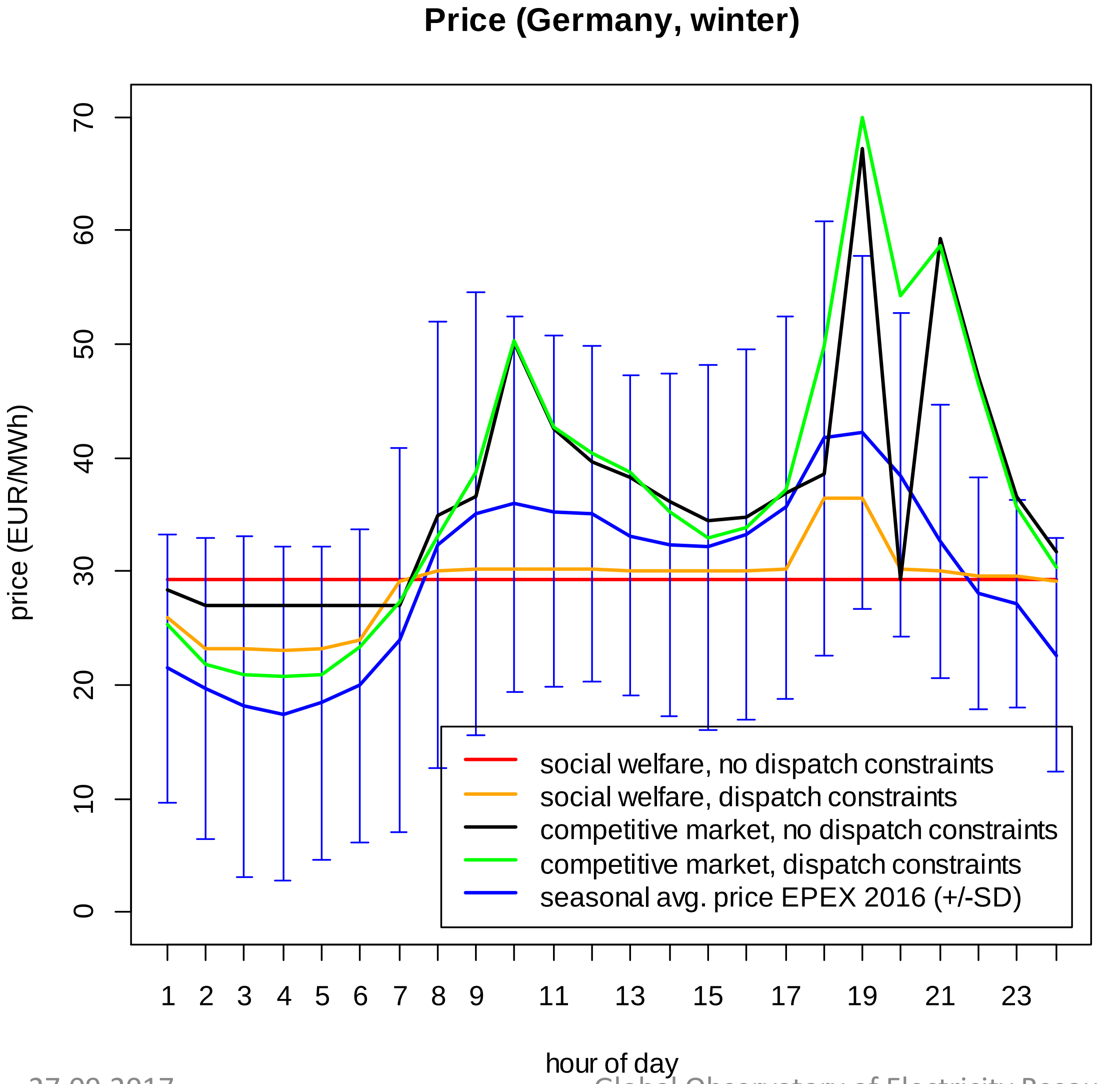
Bi-level Electricity-Market model (BEM)

- 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

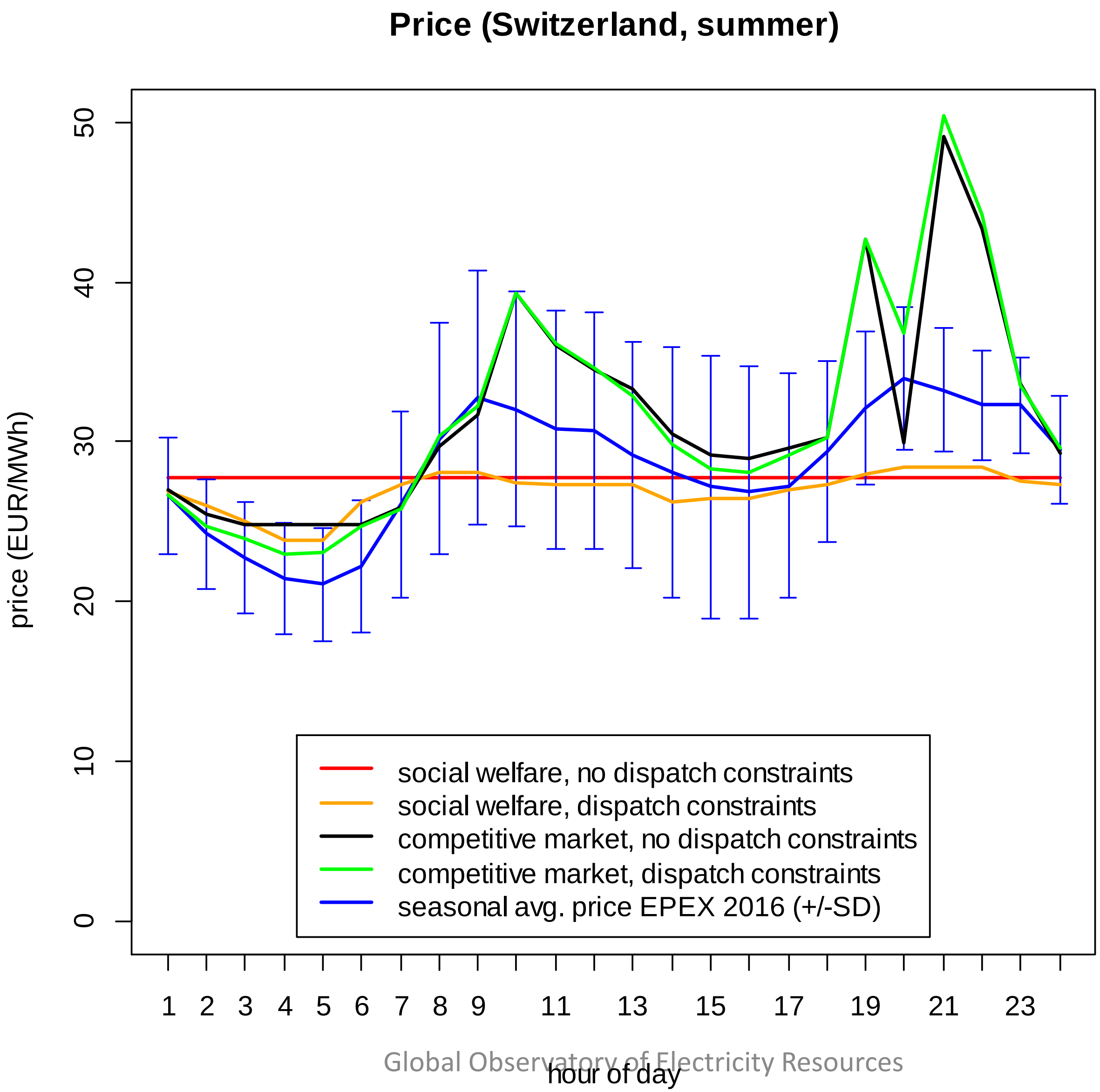


Volatility of hourly price:
(example: Winter)

	DE	CH
2016 (EPEX)	**54%**	**25%**
Social welfare maximization (without thermal constraints)	0%	2%
Social welfare maximization	13%	10%
Competitive model (without thermal constraints)	25%	26%
Competitive model	**35%**	**33%**

DE-WI Scenario with average wind & solar generation

Model validation: Switzerland



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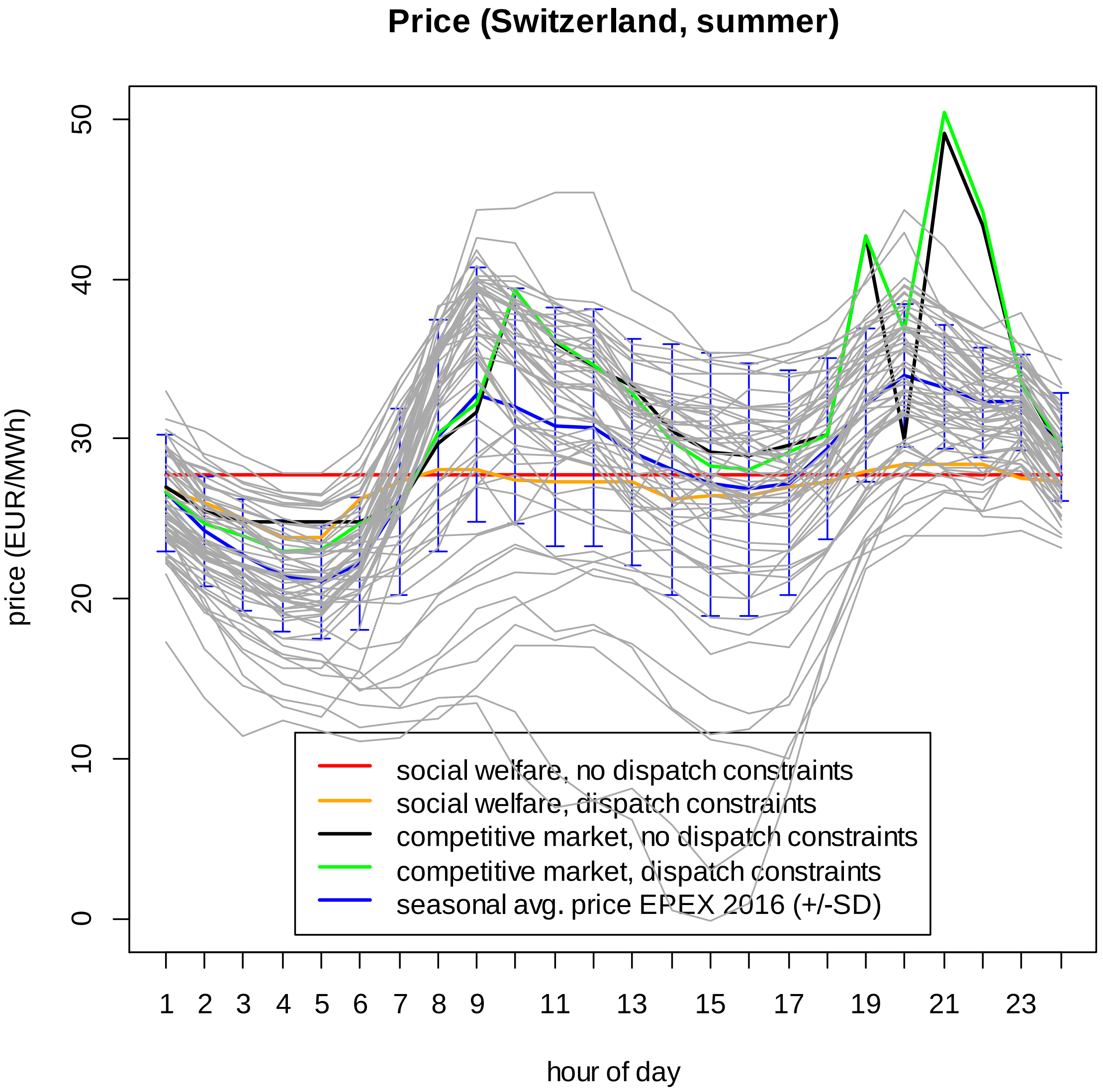
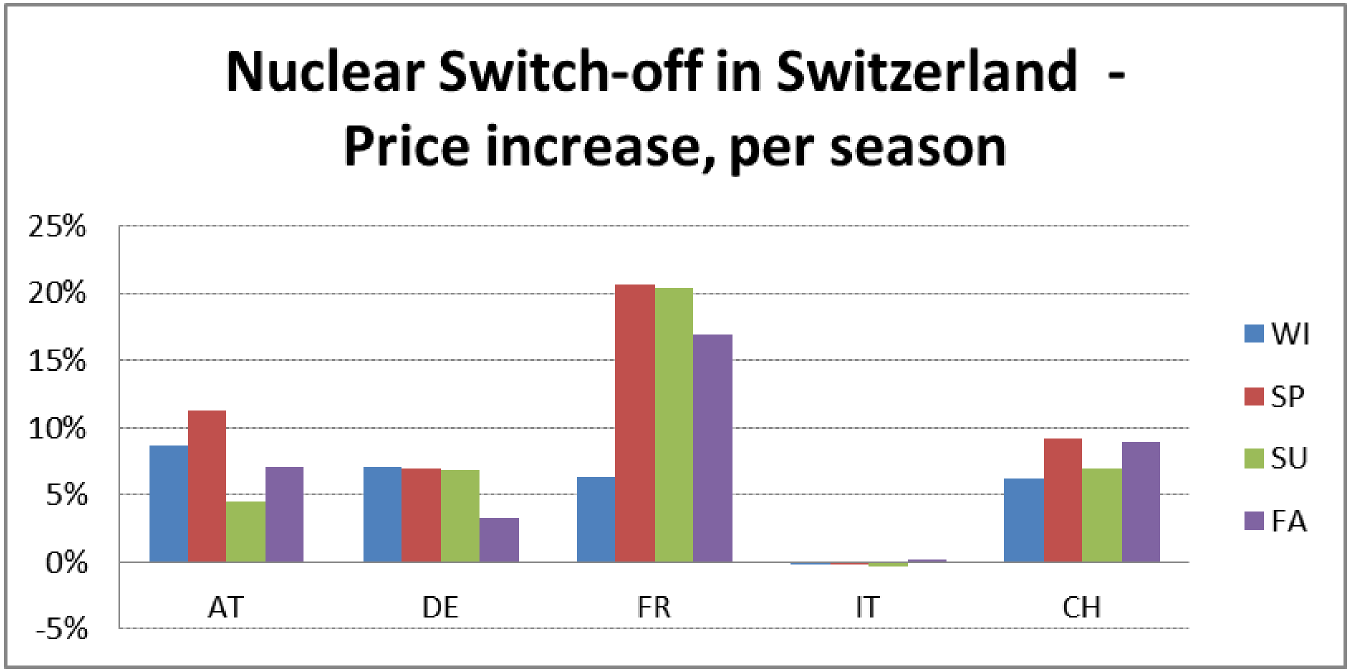


Test: Immediate nuclear switch-off in Switzerland?

Result:

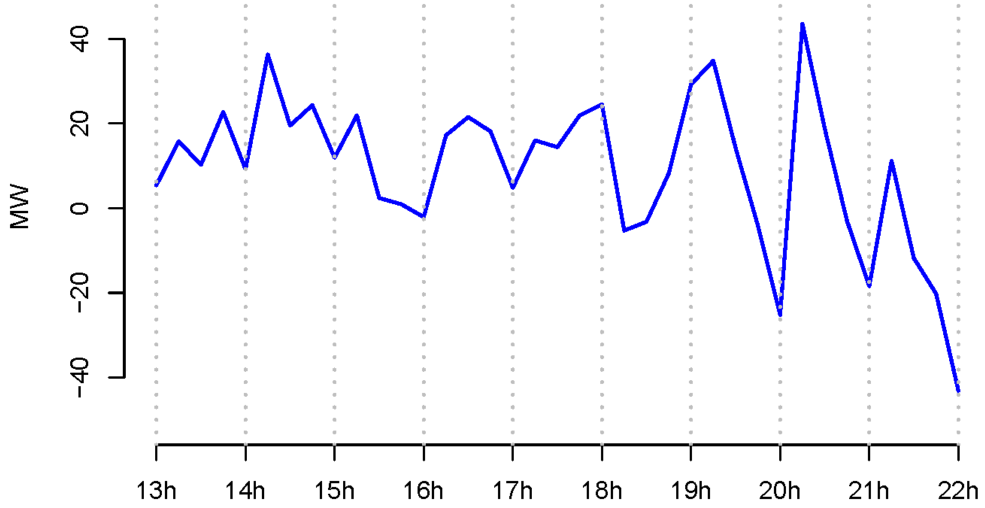
- No new investments (enough existing capacity in neighboring countries)
- CH imports more: 0.4 GW/h (avg.) ↗ 3 GW/h
- Social Welfare (over all countries, markets): −10%
- Producer’s profit: CH: −9%; avg. other countries: +22%



Nuclear Switch-off in Switzerland - Price increase, per season

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)

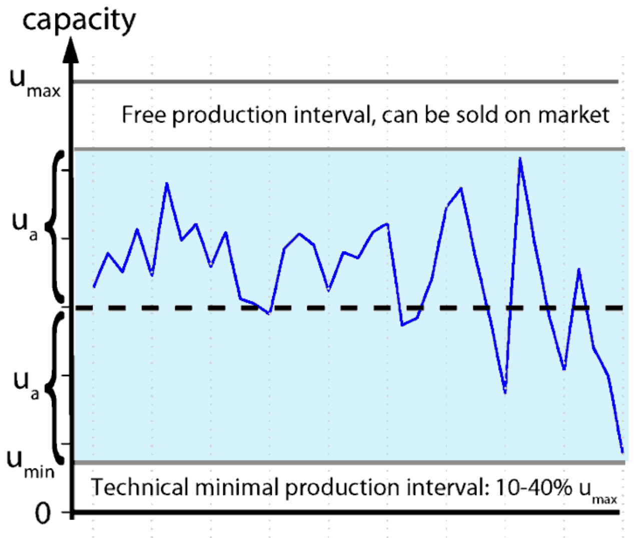


(Date: 28.3.2013)

- 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_{max} provides power ± u_a (MW) over a week; producer sells u_{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)
  - ≈1.6 Rp./MWh (in 2016) << 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:

$$\left.\begin{aligned} \max_{u(\cdot),u_a} \ & \mathbb{E}\big[S(u(S)+u_a)\big] + p_a u_a \quad \text{s. t.} \\ & \mathbb{E}[u(S)-u_a] \geq l, \\ & u(S) + 2u_a \leq u^+_{\max}, \\ & u(S), u_a \geq 0, \end{aligned}\right\}$$

Explicit solution:

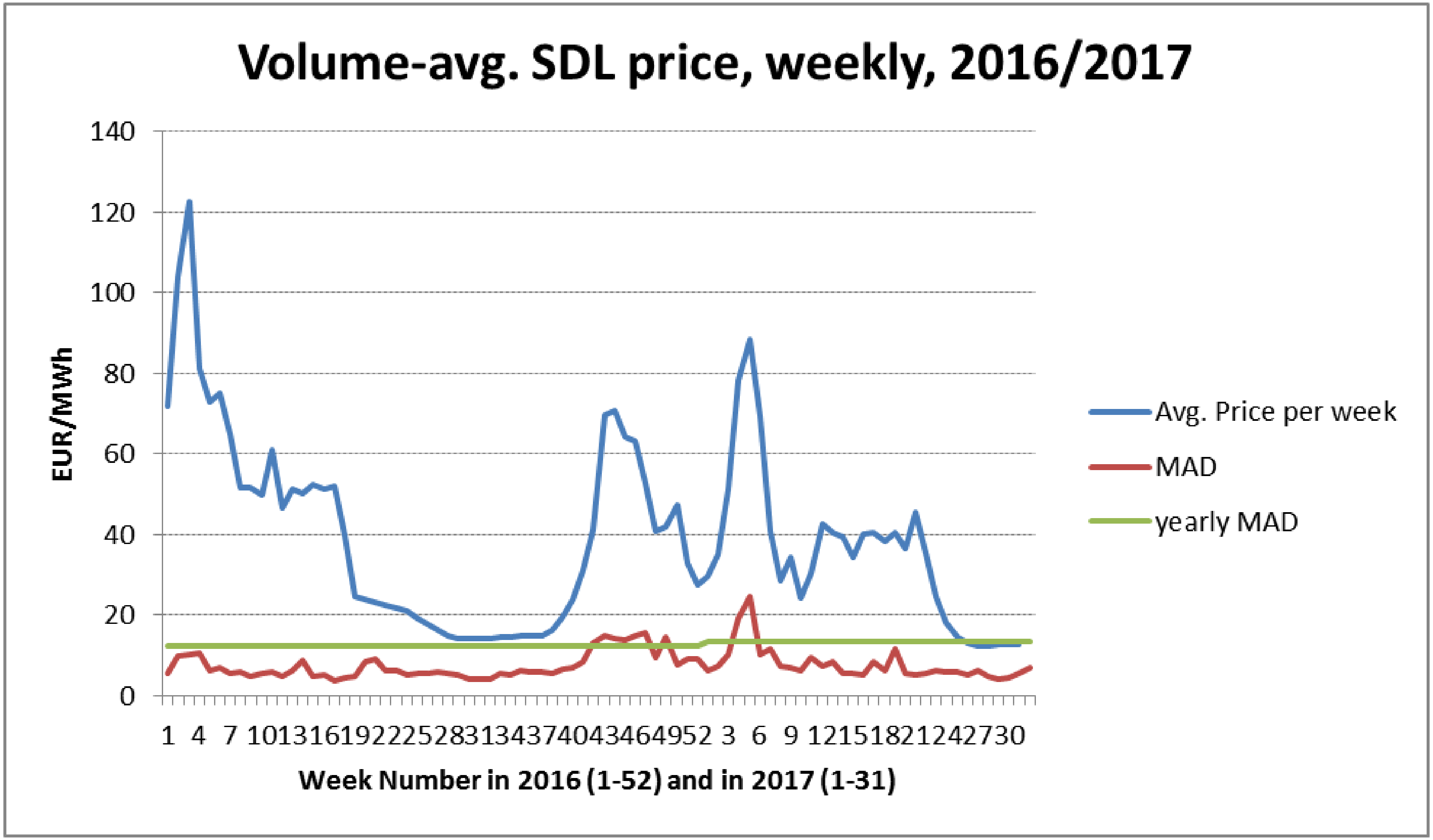
$$\hat{U} = \hat{u}(S) = \left(u^+_{\max} - 2\hat{u}_a\right) 1_{\{S \geq \hat{q}\}}$$

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

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_{max}^+: Turbine capacity (MW)
E[.]: Expectation (= average over all electricity price scenarios)

1_{S>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 ≤ q]: Probability that spot price *S* is lower or equal *q*

Auction results: Ancillary service



MAD := Mean Absolute Deviation from Median

SDL profitable >$_{\text{(strictly)}}$ MAD of spot price

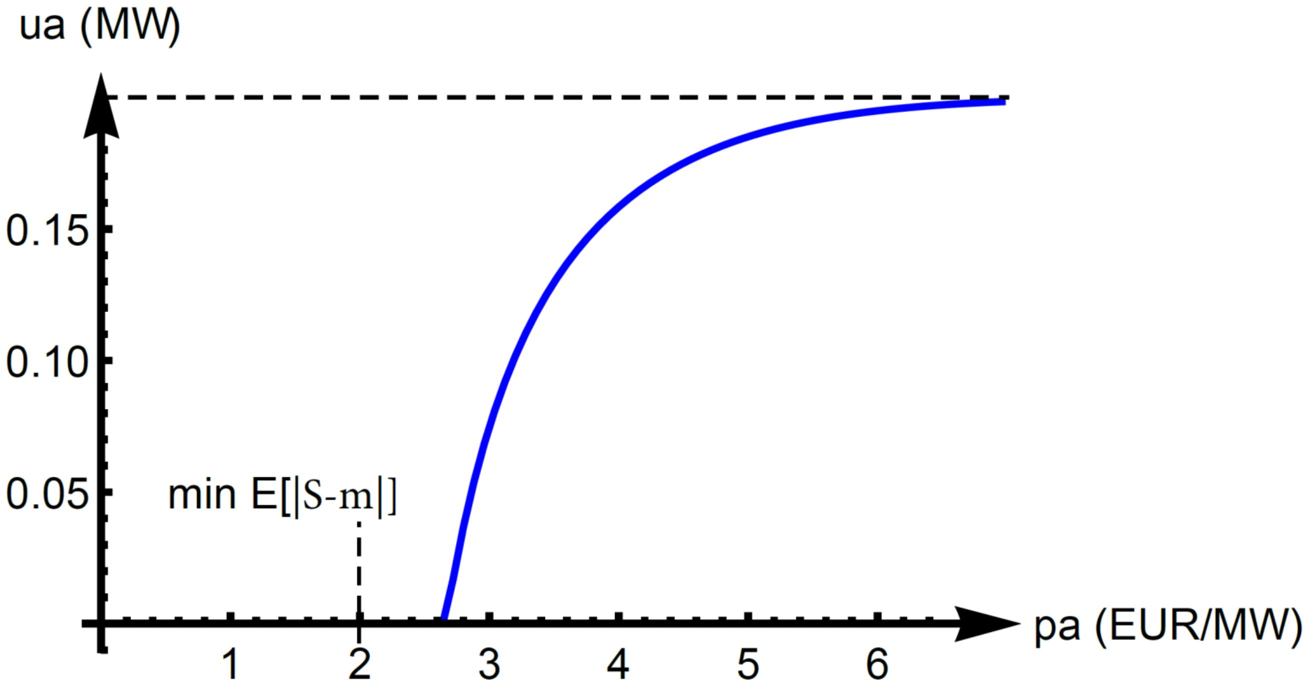


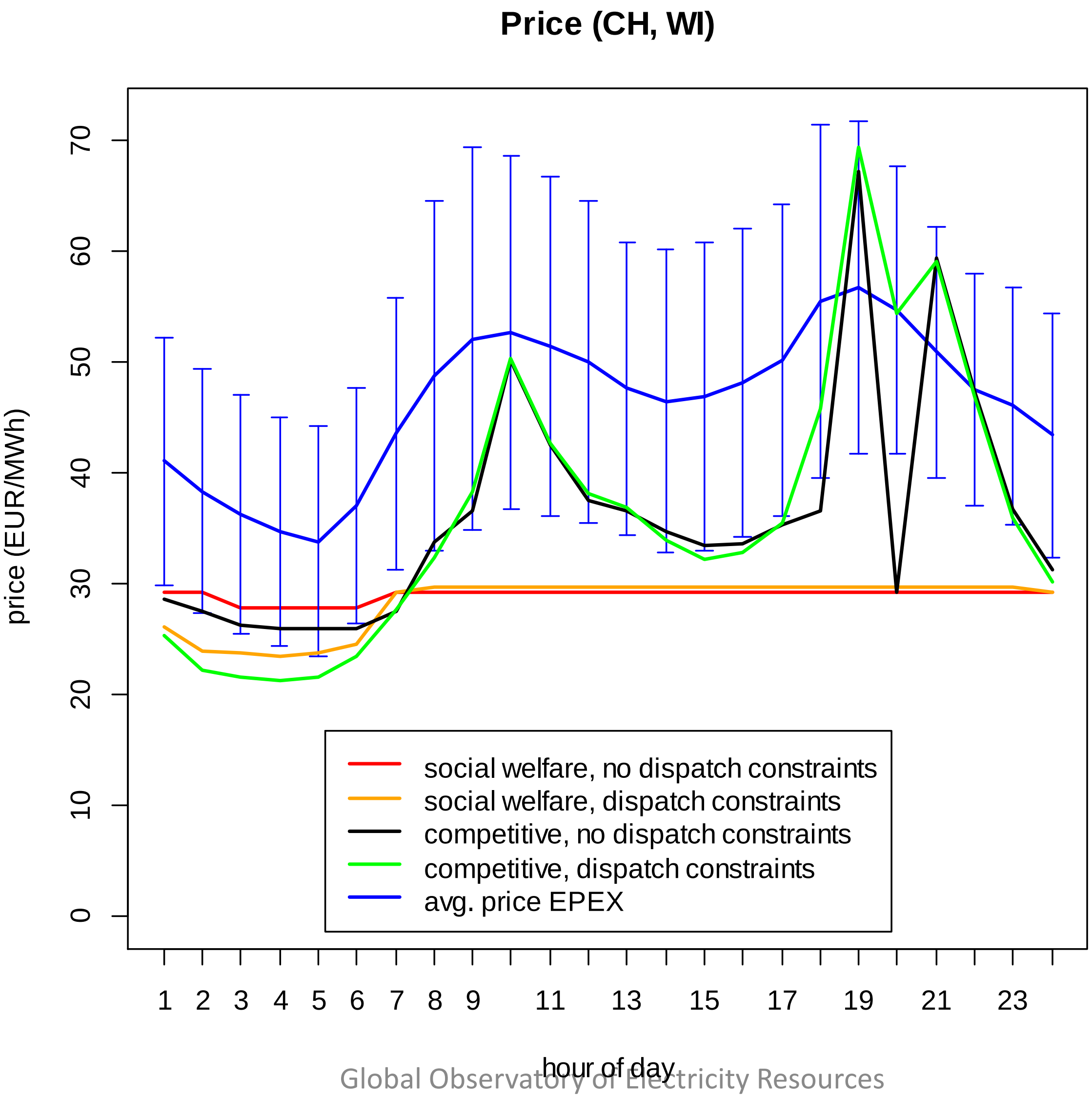
Figure 3: Ancillary service u_a as a function of the reimbursement p_a. Parameters: $u^+_{\max} = 1$; $l = 0.8$; random variable $S \sim N(10, \sigma = 2.5)$

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



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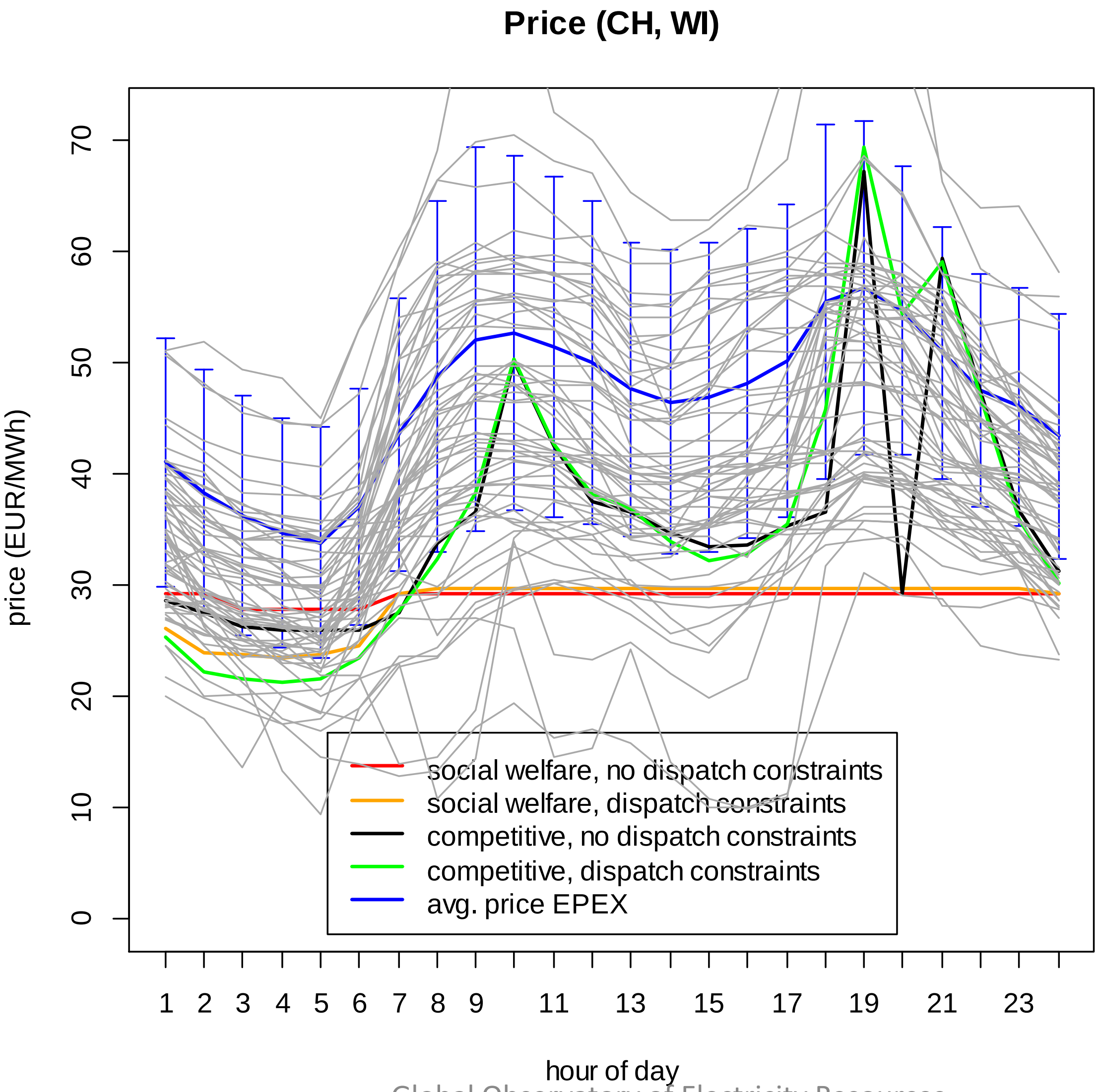
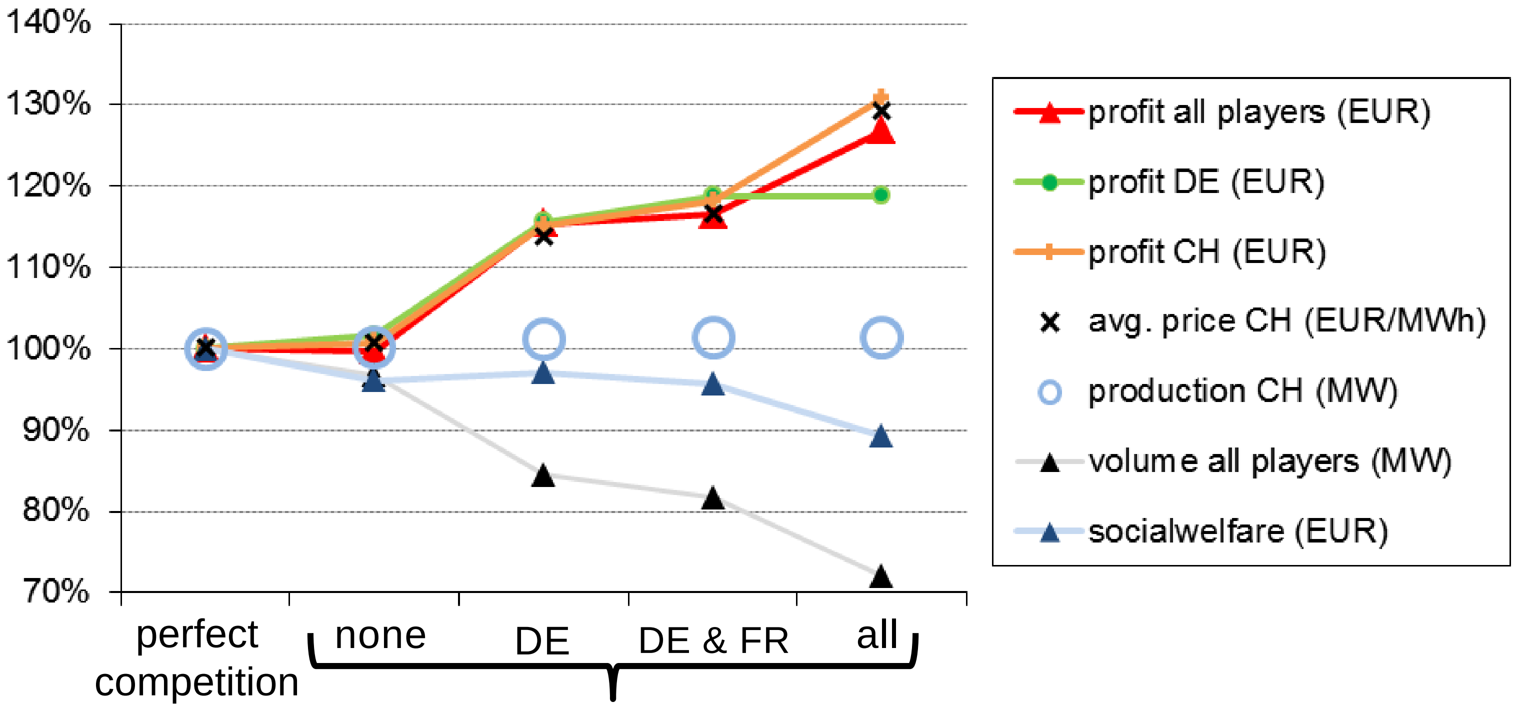


Bi-level modeling: Influence of market power

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

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

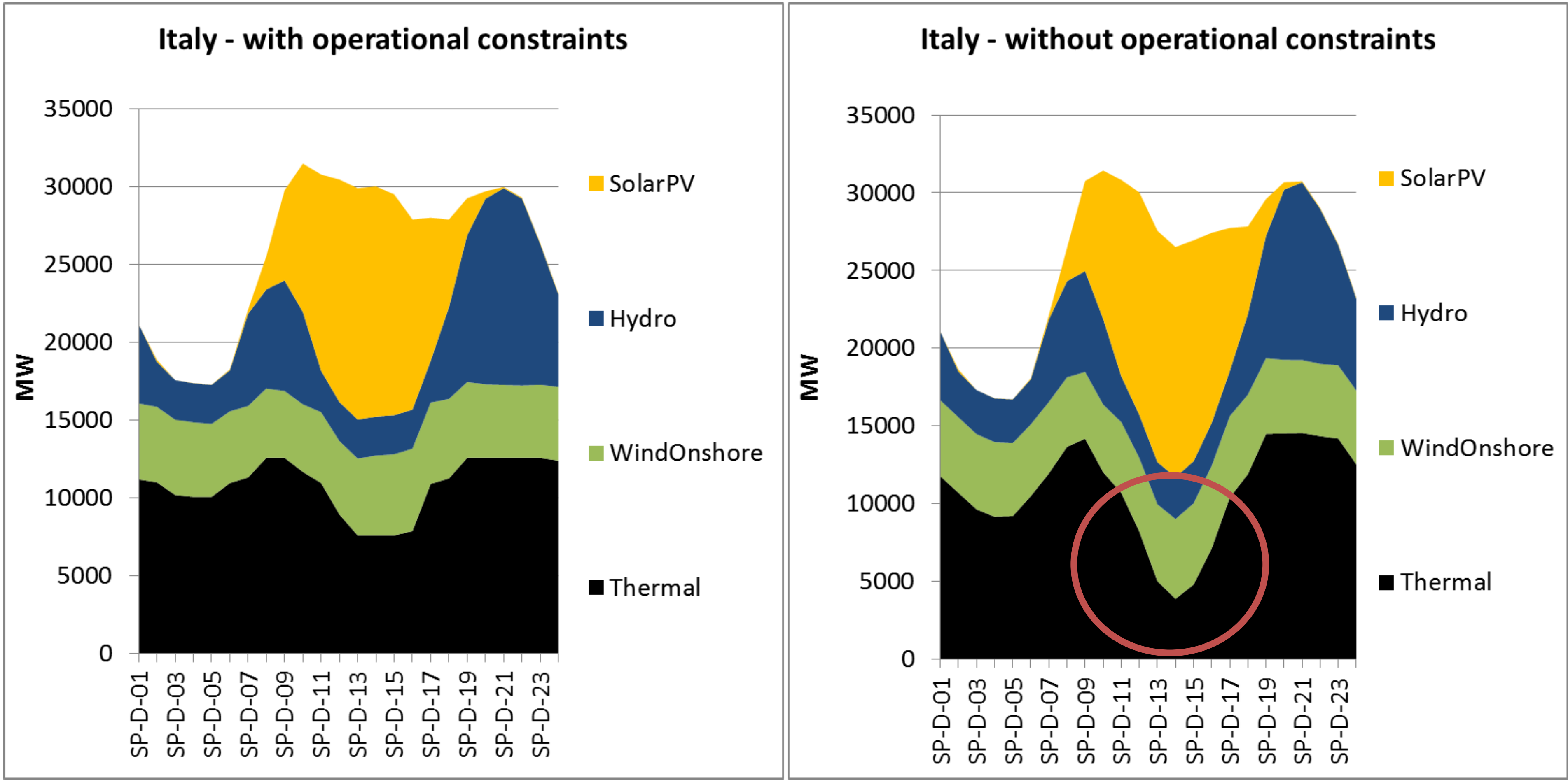
→Test influence of country’s market power on spot-market prices and volumes



players that are allowed to have market power on 2nd level (on 1st level: all players)

- **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

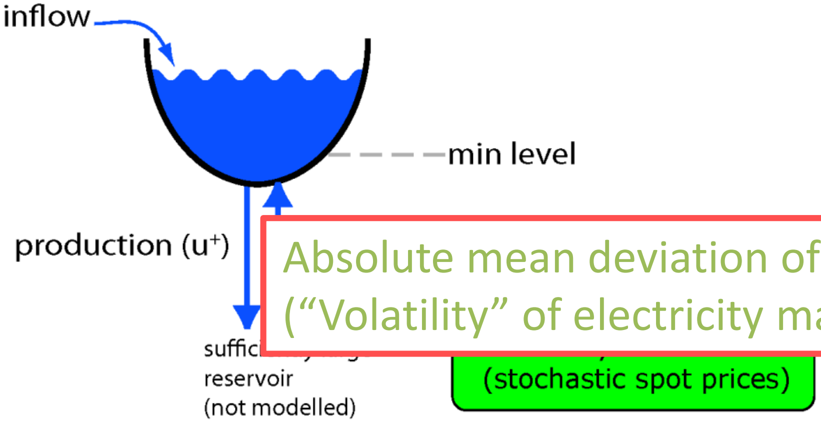
Impact of dispatch constraints of thermal generation



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



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

Ancillary service ("Systemdienstleistung"):

Storage-plant operator must decide:

- Either: Sell energy freely on spot market
- oduction capacity as ancillary
- TSO (i.e. operator loses freedom)

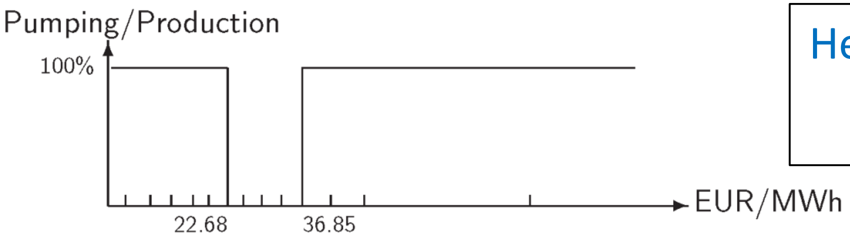
The condition is (with some simplifications):

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

- *p:* reimbursement from TSO for ancillary

Optimal dispatch is a "bang-bang" control

(using optimal control theory [LaSalle 1959]):



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*

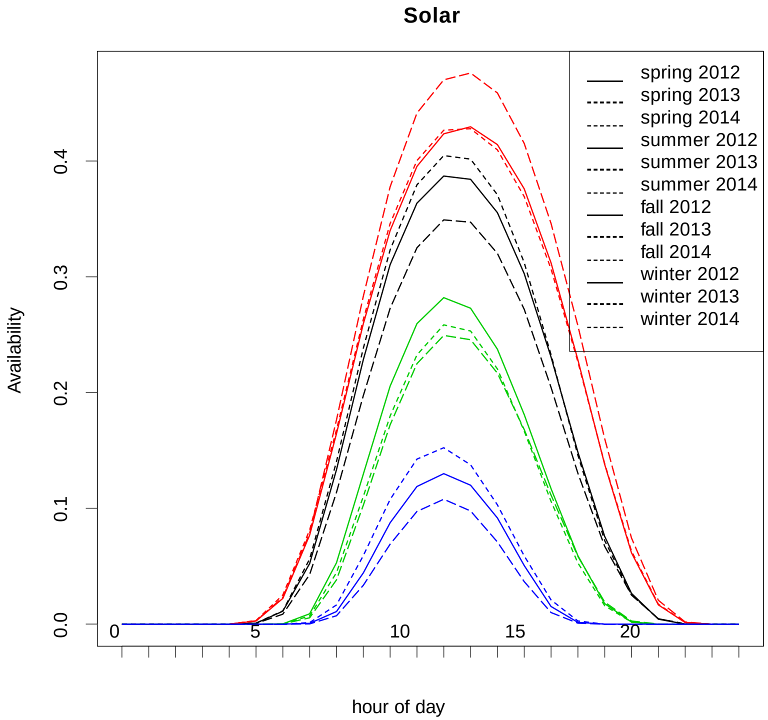
M. Densing, T. Kober (2016): Hydropower dispatch: Auxiliary services, several reservoirs and continuous time (preprint)

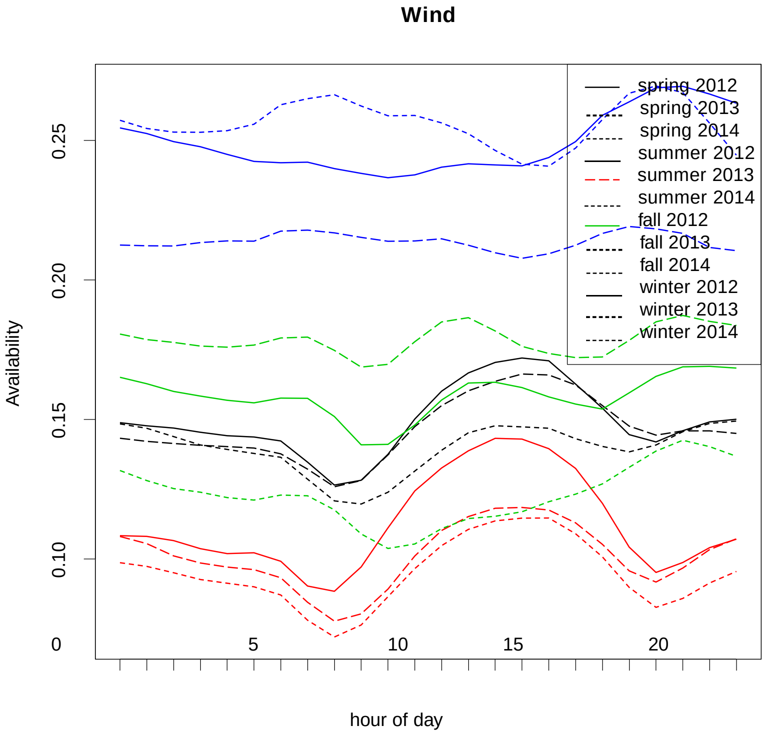
Solar and Wind

correlation	solar	wind	demand
solar	1	−0.13	0.45
wind	−0.13	1	0.088
demand	0.45	0.088	1

2012–2014, all seasons

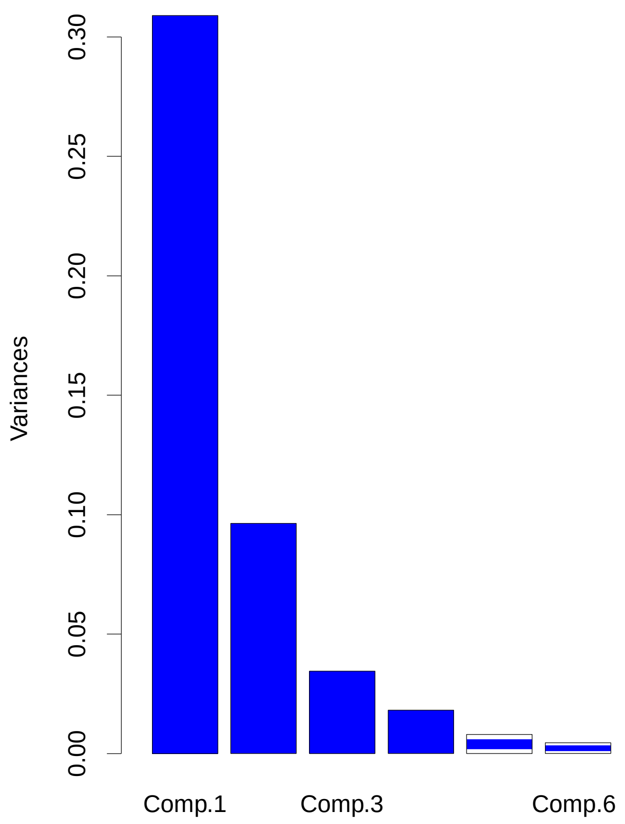
Hourly average per season and per year:

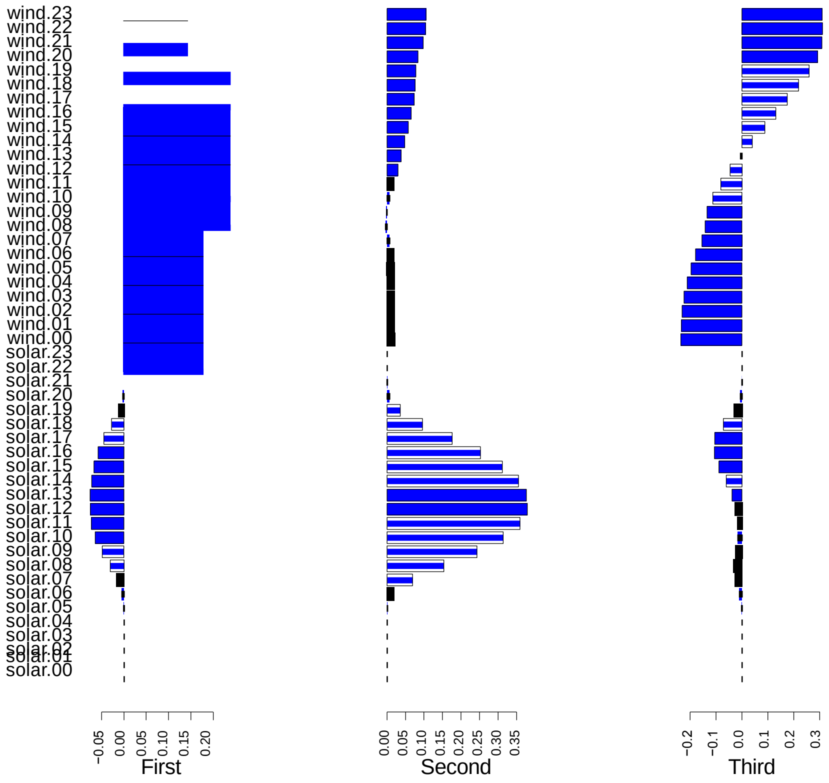




Wind+Solar Scenario Generation

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:





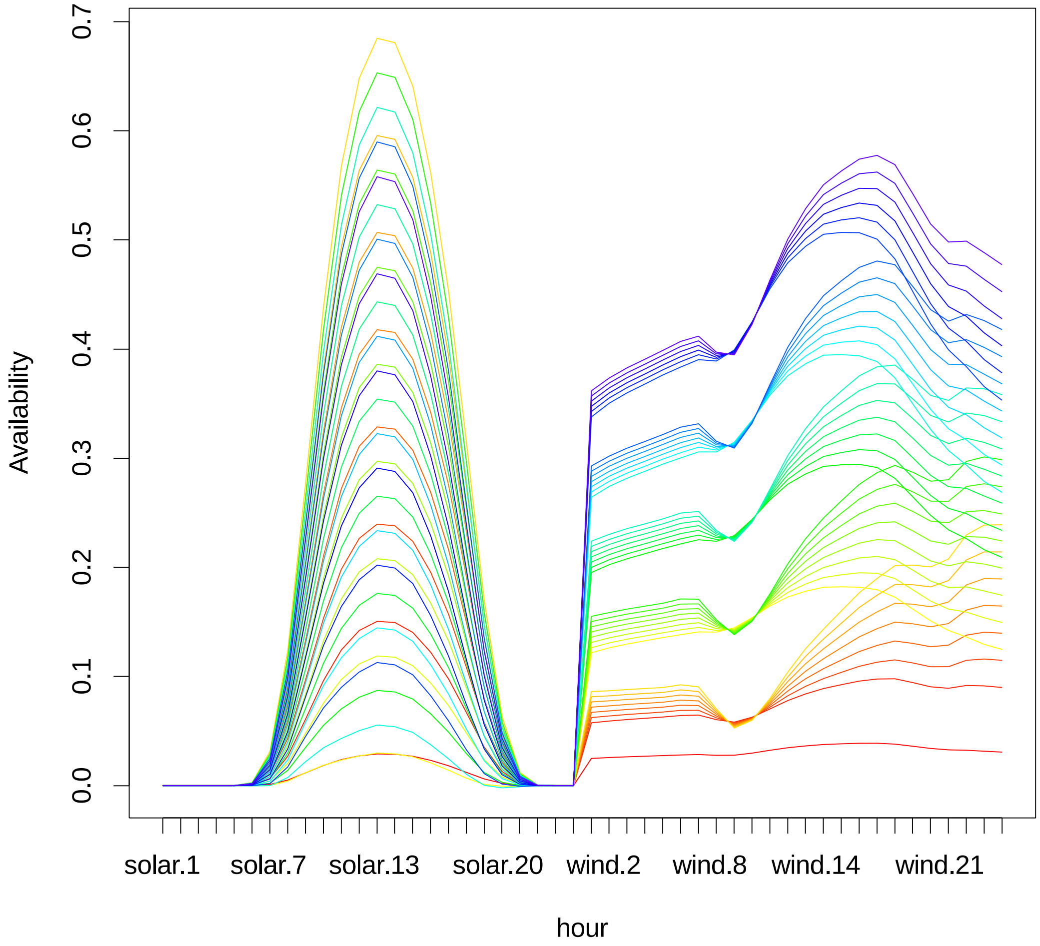
85% (92%) of variance by principal component 1.+2.(+3.)

Wind+Solar Scenarios using 1st and 2nd PCA factor

Factor model with PCA:

$$X = \Lambda F + \varepsilon, \qquad \Lambda^T \Lambda = 1,\ F \approx \Lambda^T X,\ \text{with}$$

random vectors $X, \varepsilon \in \mathrm{R}^p$, $F \in \mathrm{R}^k$, $k < p = 48$; F not correlated.



← $8 \cdot 8 = 64$ scenarios of ($k = 2$) first factors in F

- Factors assumed to be normally distributed → discretization by binomial distribution
- Raw data gives best results (i.e. w/o $\log X$, $X - \text{mean}X$) → 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

		Player 2	
		invest	do nothing
Player 1	invest	(3,3)	(1,4)
	do nothing	(4,1)	(2,2)

- The decision leading to (2, 2) is a Nash equilibrium.

Exact Solutions of Hydropower Dispatch

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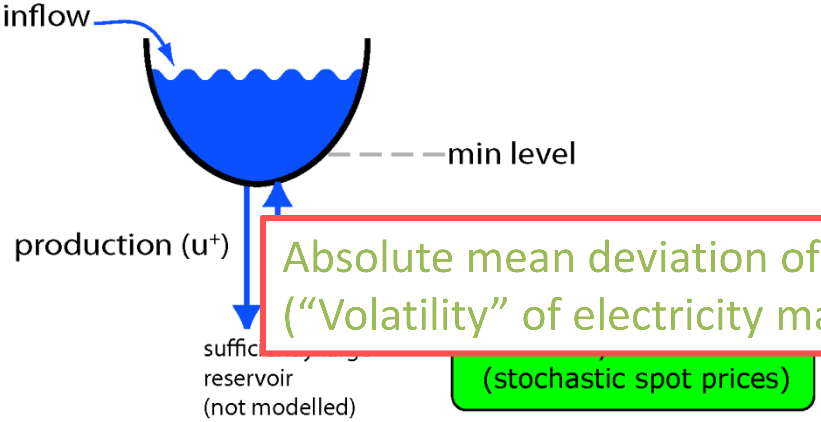

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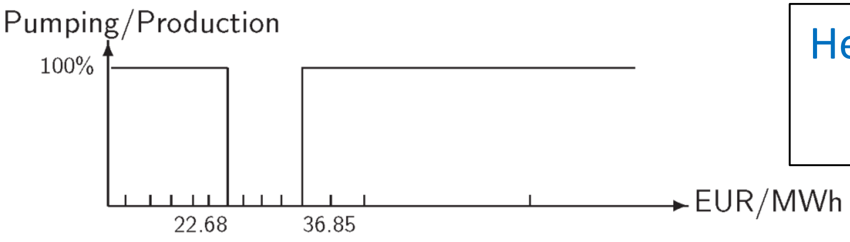

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Meta-Analysis (Example: Supply Mix 2050)

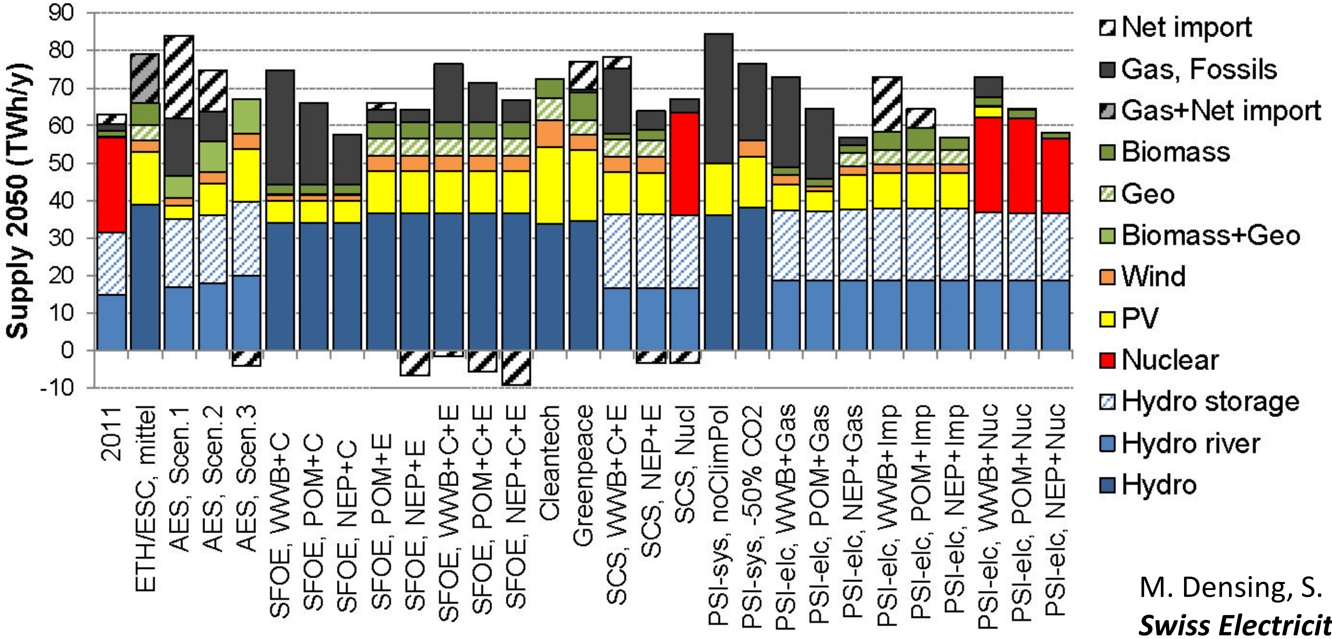
Goals of meta-analysis of a scenarios over heterogeneous studies

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?"



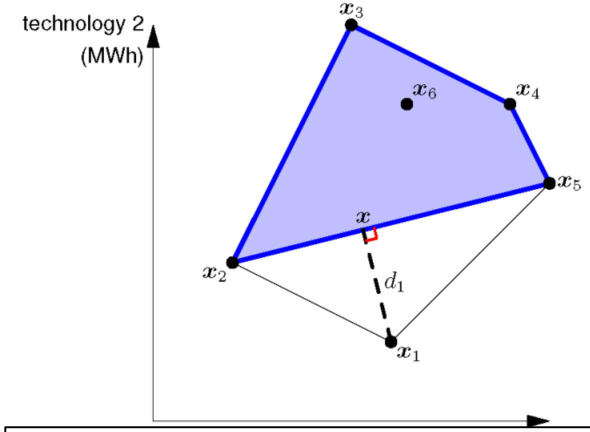
Year 2050 has relatively low annual imports across scenarios (more imports in year 2030; see report)

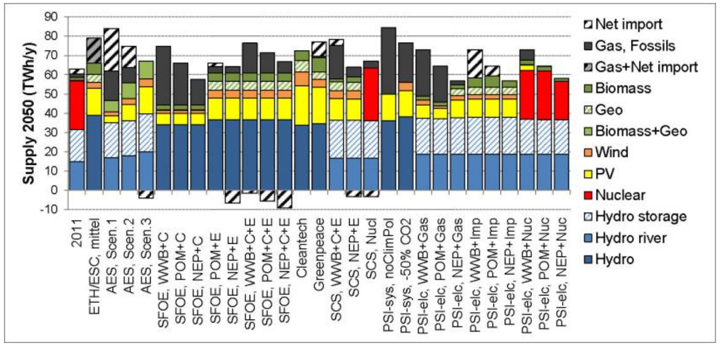
M. Densing, S. Hirschberg (2015): ***Review of Swiss Electricity Scenarios 2050***

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

→The three representative scenarios can be interpreted as major, opposite directions of energy policies in Switzerland.

ply mix of BFE’s scenario
M+C (Political measures +
ral gas-powered plant) is a
ect convex combination of
er scenarios
Possible modelling issue
Scenario may be considered
superfluous

M. Densing, E. Panos & S. Hirschberg (2016): Meta-analysis of energy scenario studies: Example of electricity scenarios for Switzerland**,** *The Energy Journal, 109*, 998-1015