Long-term Electricity Market Equilibria with Storage in the Presence of Stochastic Renewable Infeed

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Increasing interest in storage – main drivers

- Technology development
  - Particularly in Li-Ion batteries
  - But also Redox-flow batteries, Zinc-air batteries, CAES are discussed
- High-pace transition of generation landscape
- Generation adequacy with intermittent renewables being a challenge
  - Wind and PV with very low capacity credit
  - Availability of controllable thermal capacity not evident

➢ Electricity storage as a complement?

Starting point: wide range of literature

- Theoretical literature

  System perspective

  – Efficient storage operation and investment: Jackson (1973), Gravelle (1976), Steffen & Weber (2012), Lamont (2013), Böcker & Weber (2018)

  – Strategic behavior of storage and others, e.g. Sioshansi (2010)

  Individual power plant perspective

  – Deterministic storage operation: e.g. Steffen & Weber (2016)

  – Optimal storage operation under uncertainty, e.g. Sioshansi et al. (2009, 2011)

  – Optimal storage operation strategies using LSMC, ASDDP, e.g. Carmona & Ludkovski (2010), Secomandi (2010), Löhndorf et al. (2013)

- Applied work

  – Long term techno-economic analyses e.g. Sinage (2009), IEA(2013), EPRI (2013)

  – Tools for optimal operation under uncertainty using e.g. LSMC

- Combination of system perspective and consideration of uncertainties in the long-term rather rare

  ➢ Exception: Geske & Green (2016)

Research questions

- How can **optimal storage investment and operation** in the presence of **uncertainty** be described in a **system perspective**?

- What **drives** the **value of storage** in such a setting?

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Basic idea

- **Combine long-term equilibrium with short term uncertainty**

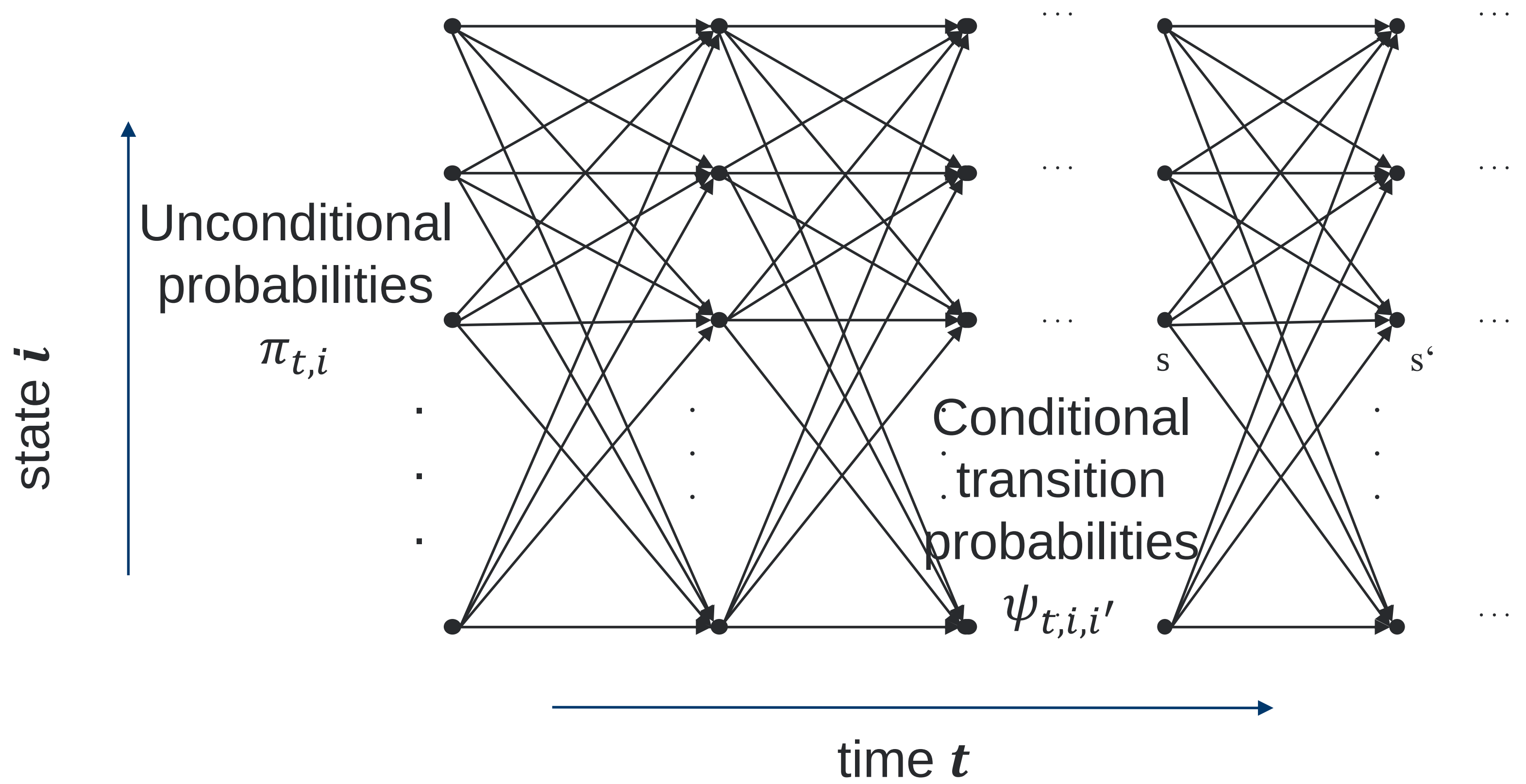
- Representation of **short-term uncertainty** through (circular) **Markov process**
  - Discrete time, discrete state representation of a mean reversion process

- Exogenous state "variable": **Residual demand**

- Endogenous state variable: **Storage filling level**

- **Long-term decision making**:
  specification of **capacities** of generators and storage **as variables**

Markov process



- To start: time-invariant probabilities $\pi_{t,i} = \pi_i$, $\psi_{t,i,i'} = \psi_{i,i'}$
- Convolution property: $\boldsymbol{\pi}^{\mathrm{T}} \boldsymbol{\Psi} = \boldsymbol{\pi}^{\mathrm{T}}$

Stylized system model – objective function

- **System cost minimization**

$$\min_{K_i, V, y_{t,i,j}, s^+_{t,i}, s^-_{t,i}} Z$$

$$Z = \sum_{t,i,j,s,s'} \pi_{t,i} c_j^{var} y_{t,i,j,s,s'} \Delta t + \sum_j c_j^{inv} K_j + c^{inv,St} V$$

With:

- $y_{t,i,j}$ production of generator *j*
- K_j capacity of generator *j*
- V volume of storage (with full-load hours *H*, i.e. C-rate 1/*H*
- $s^+_{t,i}, s^-_{t,i}$ storage charging/discharging

Stylized system model –constraints

Supply-Demand balance:

$$\sum_j y_{t,i,j} + s_{t,i}^{-} \geq D_{t,i} + s_{t,i}^{+}$$

Capacity constraints generators & storage:

$$y_{t,i,j} \leq K_j$$

$$s_{t,i}^{+} + s_{t,i}^{-} \leq \frac{1}{H} V$$

Filling level dynamics:

$$f_{t,i}^{nx} = f_{t,i} + \eta s_{t,i}^{+} + s_{t,i}^{-}$$

Filling level evolution under Markov process:

$$\sum_{i'} \pi_{t',i'} \psi_{t-1,i',i} f_{t,i}^{nx} = \pi_{t,i} f_{t,i}$$

Filling level constraints:

$$f_{t,i}^{nx} \leq V$$

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Drivers of storage investment

- **Deterministic variations of net demand**
- Predictable stochastic variations of net demand
- **Mean-reverting stochastic variations of net demand**
- Generator mix – high capex vs. high opex technologies
- Value of lost load

Technology parameters

	Capacity costs	Other fix costs	Fuel cost	Efficiency	Emission intensity	Operational costs
	k€/MW	k€/MW/a	€/MWh_{th}	%	t_{CO2}/MWh_{th}	€/MWh
Lignite	1800	0	4	43%	0.4	27.91
Hard coal	1600	0	7	45%	0.34	30.67
CCGT	800	0	25	60%	0.2	48.33
OCGT	500	0	25	35%	0.2	82.86
VoLL	0.01	0	10000	100%	0	10000
Li-Ion	100 k€/MWh	0		90%	--	--

- *Annuity factor 0.1, further downscaled to one representative day*
- *Exogenously set CO_2 price: 20 €/t*

Demand specification

- **One representative typical day**
- **Six time intervals** of four hours each
- **Sinuisoidal deterministic demand** component

$$\mu_t^D = \mu_0 + a \cdot \sin(\psi t + \theta)$$

- **Mean-reverting stochastic** demand component

$$dx_t = -\kappa \cdot x_t \cdot dt + \sigma \cdot dW_t$$

- Total demand

$$D_t = \mu_t^D + x_t$$

- In discrete time

$$D_t^{|x_{t0}} \sim N\left(\mu_t^D + e^{-\kappa(t-t0)} x_{t0}, \frac{\sigma^2}{\kappa} \cdot \left(1 - e^{-2\kappa(t-t0)}\right)\right)$$

Demand parameters

- Mean demand: μ_0= 65 GW
- Amplitude deterministic variation: a = 15 GW
- Phase angle deterministic variation: $\theta = \frac{\pi}{2}$
- Mean reversion speed: $\kappa \approx \frac{1}{3 \cdot 24\ h}$
- Some approximations needed for discretization
- Resulting unconditional and conditional probabilities

$$\Pi_t = \begin{pmatrix} 0.003 \\ 0.242 \\ 0.509 \\ 0.242 \\ 0.003 \end{pmatrix}, \Psi_t = \begin{pmatrix} 0.918 & 0.082 & 0 & 0 & 0 \\ 0.001 & 0.957 & 0.042 & 0 & 0 \\ 0 & 0.020 & 0.960 & 0.020 & 0 \\ 0 & 0 & 0.042 & 0.957 & 0.001 \\ 0 & 0 & 0 & 0.082 & 0.918 \end{pmatrix}$$

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Sensitivities considered

1) Cases ***Reference***
   – As described above
2) Case ***No deterministic variation***
   – Sinusoidal variation set to zero
3) Case ***No mean reversion***
   – Persistence of demand level, no short term stochastics
   – Mean-reversion set to zero, i.e. transition matrix with 1′s on the diagonal
   – Corresponds to limiting case
4) Case ***Full mean reversion***
   – Full unconditional stochastic uncertainty applies in each time step
   – Conditional distribution is equal to unconditional distribution
5) Case ***No determ. & Full MR***
   – Combination of cases 2) and 4)

➢ Unconditional stochastic distribution is identical in all cases

Optimization results

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[GW]	Reference	No determ. Variation	No mean reversion	Full mean reversion	No determ. & full MR
Lignite	55.0	55.0	55.0	66.3	65.3
Hard Coal	9.7	10.0	10.0	0.0	0.0
CCGT	10.3	10.0	10.0	0.0	0.0
OCGT	11.2	10.0	11.3	0.0	0.0
Lost Load	0.0	0.0	0.0	0.0	0.0
Total Gen	86.2	85.0	86.3	66.3	65.3
Storage	**23.4**	**0**	**23.4**	**46.7**	**29.0**
Total Gen + Stor	**109.6**	**85.0**	**109.7**	**113.0**	**94.3**
Max Demand	98.0	85.0	98.0	98.0	85.0
System Cost [M€]	91.9	88.6	91.9	89.3	86.6

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Storage Usage – precautionary storage

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	Reference	No determ. Variation	No mean reversion	Full mean reversion	No determ. & full MR
Storage [GWh]	**93.5**	**0**	**93.5**	**186.6**	**115.9**
Filling Level $f_{t,i}$					
Minimum	0%		0%	43%	68%
Maximum	100%		100%	95%	68%

- Cases *Reference* and *No mean reversion*:
  Low stochastics, available storage volume is fully used in planning
  - ➢ **No precautionary storage**
- Case *Full mean reversion*
  stochastic and deterministic components in variation
  - ➢ **precautionary storage** accounts for about half of storage volume
- Case *No determ. & Full MR*
  - ➢ **only precautionary storage**, since no predictable variation

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Case Study - Key elements

- German **time series for three full years** (period 07/2016 – 06/2018)
  - Load
  - Wind onshore & offshore
  - Solar
- Taken from smard.de, load scaled to annual electricity consumption in GER
  - Computation of net load for each observation
- Construction of **one representative day**
  - **Hourly time intervals**
  - **10 net load levels**
  - Specific load levels per hour, corresponding to **deciles of the hourly distribution**
- Probabilities
  - Unconditional probabilities by construction all equal to 0.1
  - **Conditional probabilities** obtained by counting **empirical state transitions** (not hour-specific)

Case Study - Key results

[GW]	Reference
Lignite	34.0
Hard Coal	11.5
CCGT	17.0
OCGT	2.7
Lost Load	0.0
Total Gen	65.2
Storage	**16.3**
Total Gen + Stor	**81.4**
Max Demand	75.4
System Cost [M€]	70.6

	Reference
Storage [GWh]	**65.2**
Filling Level $f_{t,i}$	
Minimum	5.1%
Maximum	99.9%

- Storage part of the efficient portfolio
- **Precautionary storage** corresponding to **5 % of storage volume**

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Final remarks

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- **Long-term electricity market equilibrium including impact of short-term uncertainties** can be formulated as **stochastic linear program**
  - Greenfield approach used here
  - Could be extended to multiannual expansion planning
- **Profitability of storage** depends on
  - **Deterministic variations of net demand**
  - Predictable stochastic variations of net demand
  - **Mean-reverting stochastic variations of net demand**
  - Generator mix
  - Value of lost load
- **Precautionary storage** gets important
  with **low deterministic and high stochastic, unpredictable fluctuations**
  - Case study for Germany suggests currently 5 %
  - ➢ Adequate description of net demand including several deterministic and stochastic processes required

Thank you for your interest

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