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Optimal Storage Investment and Management under Uncertainty

It is costly to avoid outages!

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Motivation

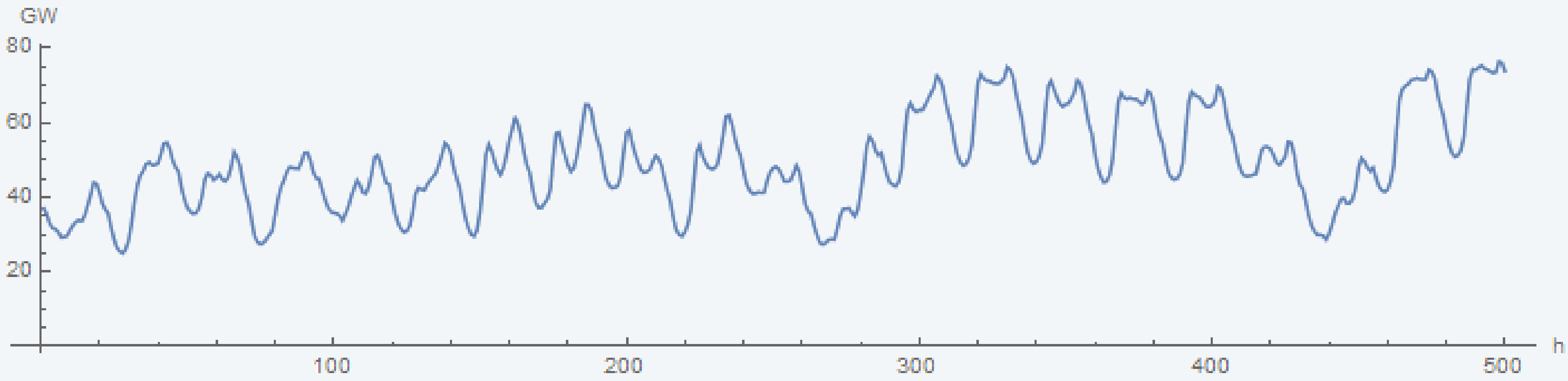
- Storage: potential to increase efficiency of electrical systems - especially in the context of integrating intermittent renewable technologies.
  → Shifting energy from periods of **low** to periods of **high** demand.
  → Utilization of medium load plants is **increased** and the utilization of peak load power plants is **reduced**.
  → Full extent of efficiency gain if capacity is adapted - higher base load and lower peak load share.
- Installed fossil generation capacity falls below peak load level.
- Limited energy stored → risk of outages in cases of prolonged demand peaks.
- Not analysed systematically in perfect foresight analyses (paradigm)

→ How is storage operated optimally under renewable and load uncertainty in the system context?

Optimal Storage Investment and Management under Uncertainty - It is costly to avoid outages!

1. Markov representation of residual load (= Load – Renewable Generation)
2. Economics of storage under perfect foresight
3. Economics of storage under load uncertainty
   a. Stochastic electricity system model with non- intermittent generation and storage
   b. Simulation of optimal strategies
4. Comparison cost savings potential of storage
5. Conclusion

1. Markov representation of residual load

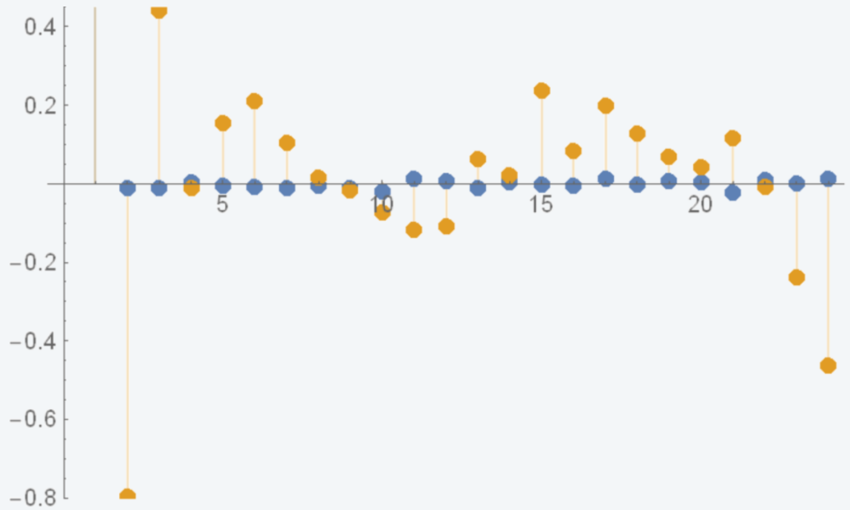


Original data, Germany 2014

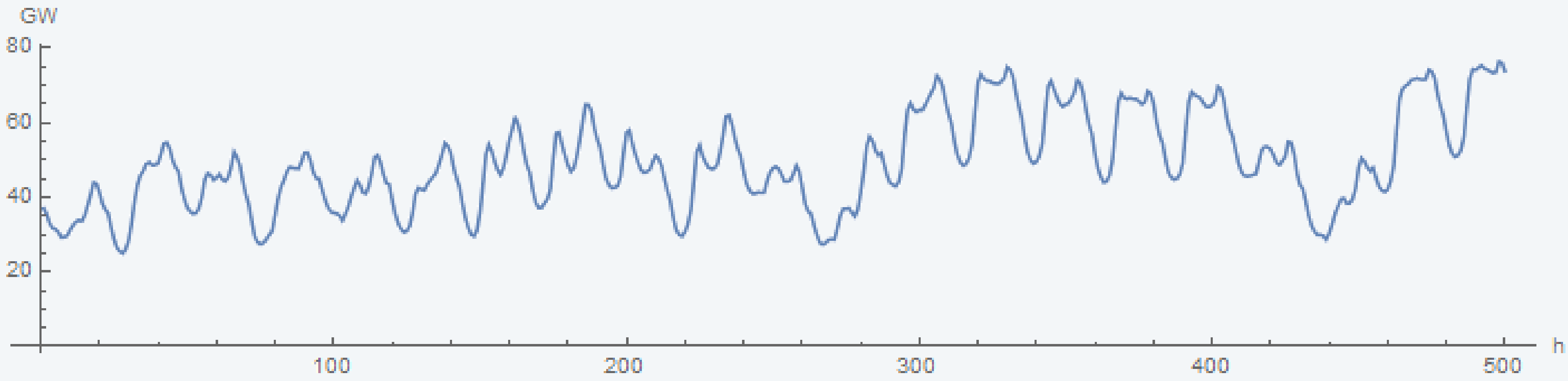
Estimated Markov chain

$$P = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.02 & 0.79 & 0.19 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.03 & 0.8 & 0.17 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.05 & 0.81 & 0.14 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.12 & 0.76 & 0.12 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.2 & 0.73 & 0.07 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.22 & 0.77 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.45 & 0.55 \end{pmatrix}$$

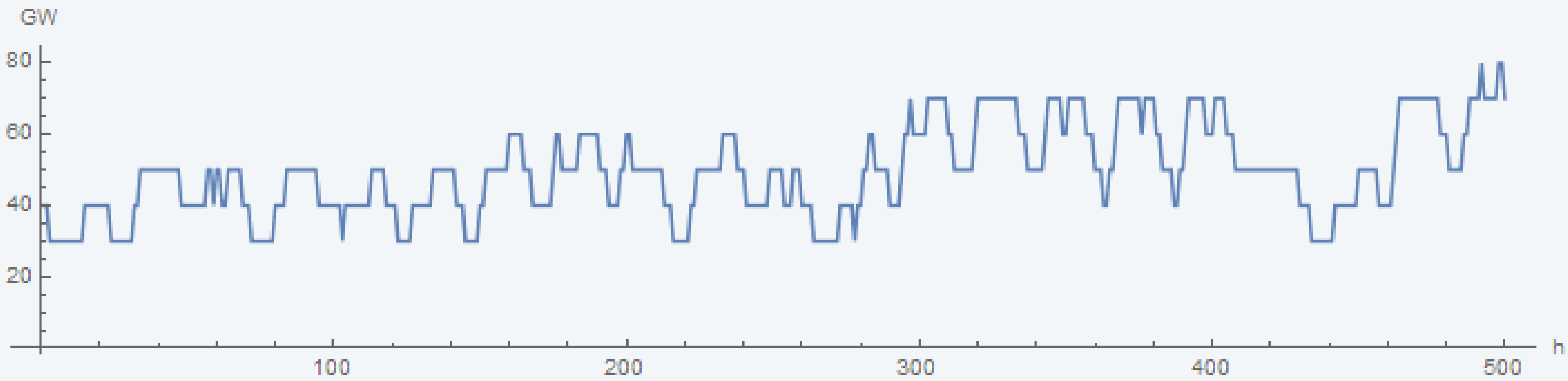
Partial Autocorrelation Coefficient



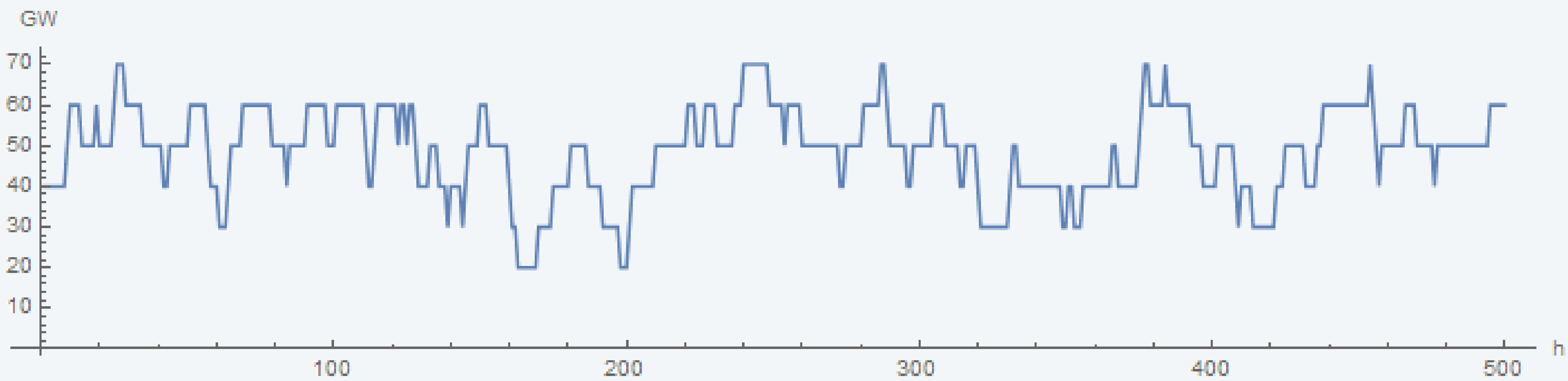
2. Markov representation of residual load



Original data, Germany 2014



Rounded original data

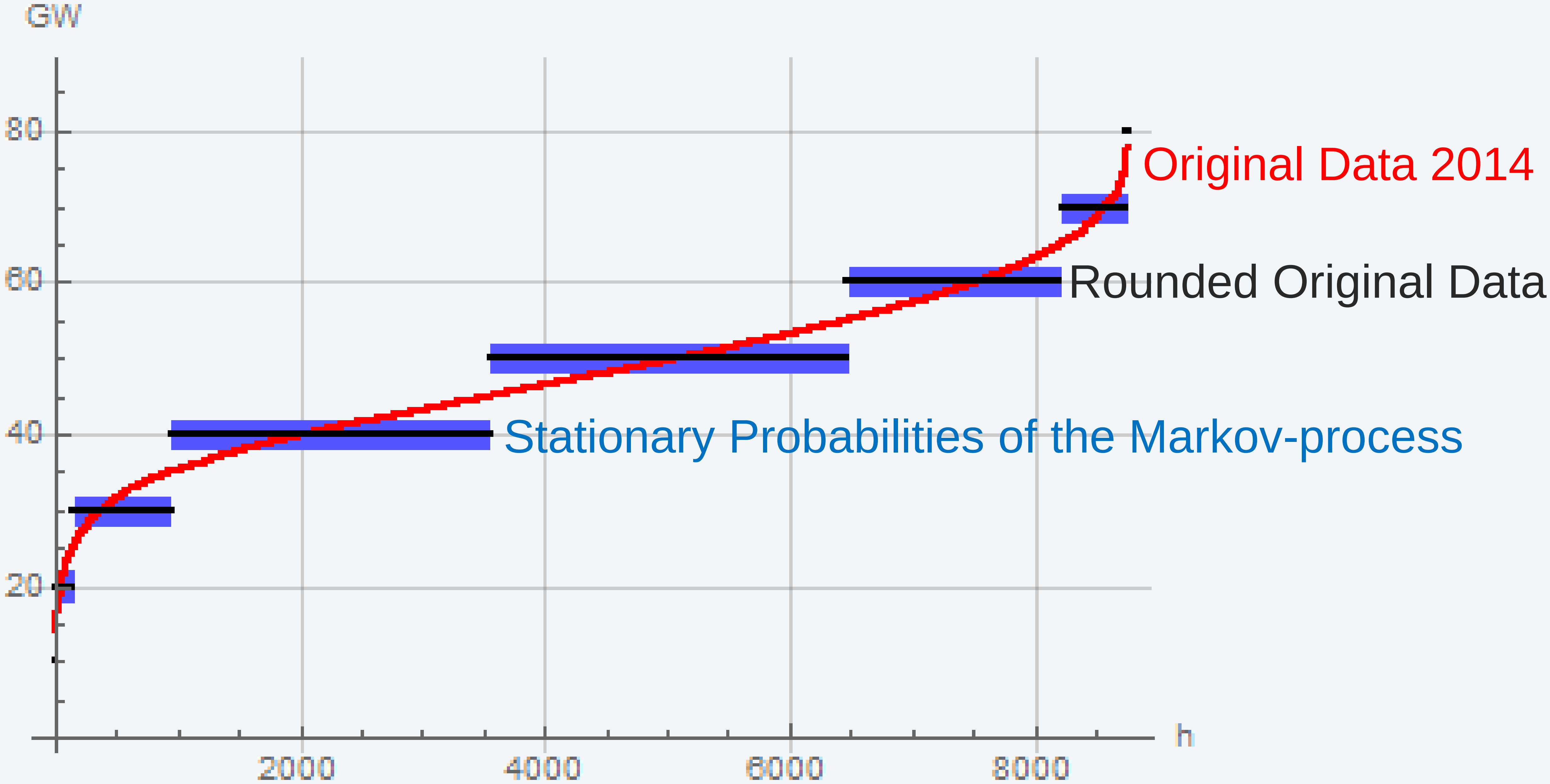


Markov-process draw

1. Markov representation of residual load

Load duration curve

- Residual load of Germany 2014



→ almost perfect fit

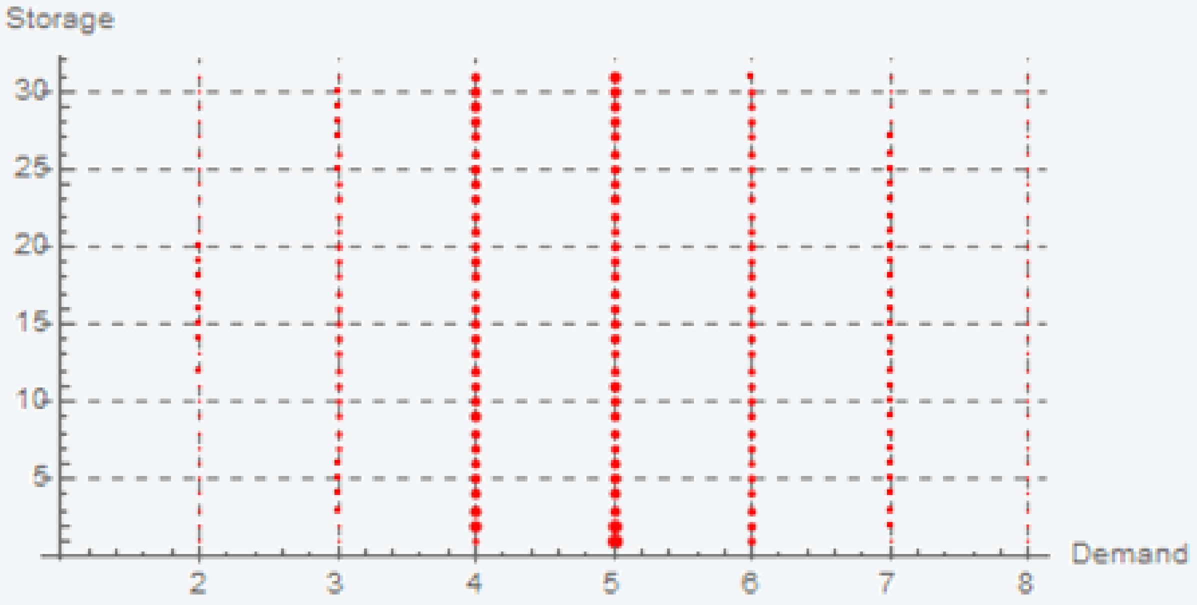
2. Economics of storage under perfect foresight

- Most simple linear electricity system model

$$\min_{x_t,k,s_t} c^{fix} k + \frac{\mu_{Det}}{T} \sum_{t=1}^{T} c^{var} x_t$$

  - Resource constraint
  - Cumulated energy stored
  - Generation capacity constraint
- Value of Lost Load for undersupply
- Costs and Load: Germany 2014
- 300 GWh of storage, used to minimize cost
- Predicted Cost:

Distribution of states



		Without storage	300 GWh storage	Change in system cost
Perfect foresight	Residual load 2014	570.8	550.0	-3.6%
Perfect foresight	Simulated Load	559.0	534.2	-4.4%

3. Economics of storage under load uncertainty

Model

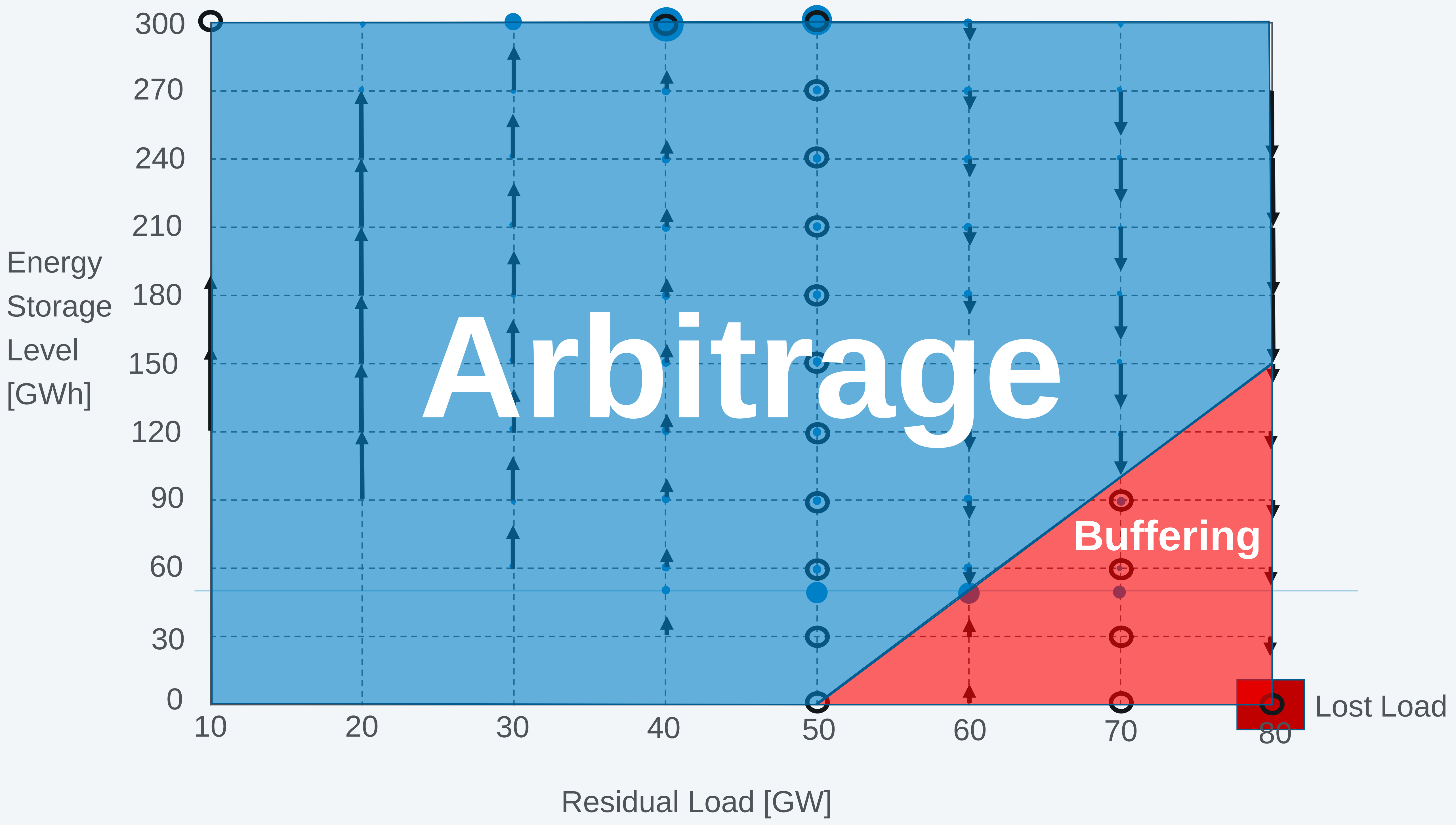
- Most simple stochastic electricity system model

$$\min_{k,\pi} c^{fix}k + \mu_{Sto} \lim_{T\to\infty} \frac{1}{T+1} \mathrm{E}\left[\sum_{t=0}^{T} c^{var}x_t + VoLL(D_t + s_t - x_t)^+\right]$$

- VoLL option
- What is a solution? Decision rule or strategy
- Numerical solution of a series of Markov Decision Problems (MDP) for strategy and stationary probabilities | capacities
- Case: 300 GWh storage option

3. Economics of storage under load uncertainty

Optimal policy/strategy – 70 GW capacity



4. Comparison

Capacities [GW]

1. Storage is not used completely for arbitrage (buffering):
   No unloading <= 50 GWh - only in the 80 GW load case
   → 50 GWh reserve for peak load
2. If storage is used for buffering, the system has to serve a higher load for a longer period and capacities cannot be adapted "completely".

	Perfect foresight Residual load 2014		**Perfect foresight Simulated Load**		**Stochastic Model Simulated Load**	
GW	Without storage	300 GWh storage	Without storage	300 GWh storage	Without storage	300 GWh storage
Nuclear	41.0	45.6	40.0	44.5	40.0	50.0
IGCC	13.0	8.1	0.0	0.0	0.0	0.0
Coal	9.0	4.4	10.0	5.9	10.0	0.0
CCGT	0.0	0.0	20.0	5.6	20.0	20.0
Combustion Turbine	13.0	5.5	0.0	0.8	10.0	0.0
Total	76.0	63.6	70.0	56.8	80.0	70.0

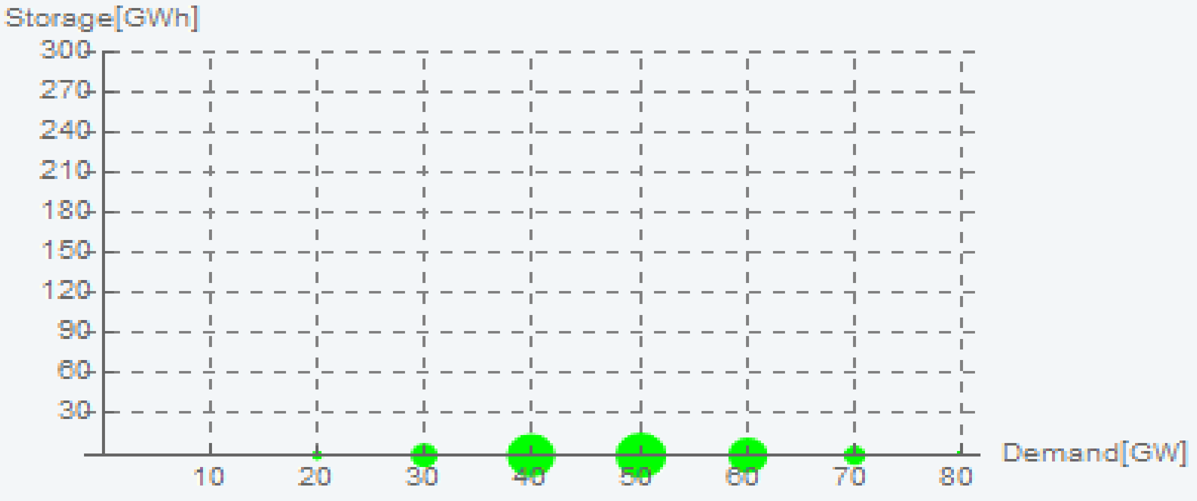
- Reduction of installed capacities (-12.4 GW, -13.2 GW, -10 GW)
- Higher baseload (+4.6 GW, +4.5 GW, +10 GW)

3. Economics of storage under load uncertainty

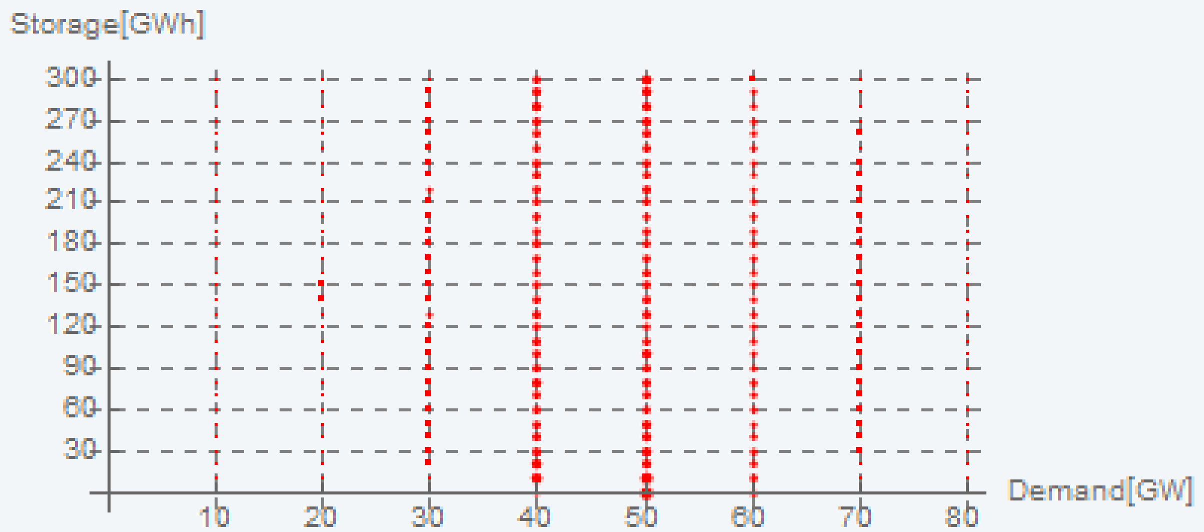
Stationary probabilities

Without storage

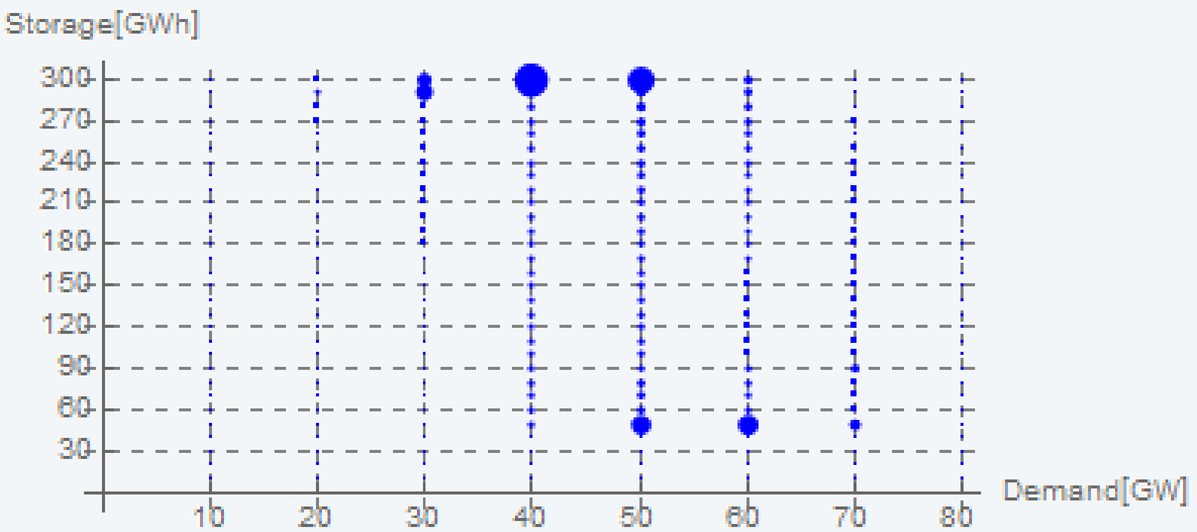
stationary probabilities = load duration



Perfect foresight



Load uncertainty



3. There is more “waiting”

4. Comparison / Conclusion

Total System Cost [10^9 €]

		Without storage	300 GWh storage	Change in system cost
Perfect foresight	Residual load 2014	570.8	550.0	-3.6%
Perfect foresight	Simulated Load	559.0	534.2	-4.4%

- Compared to perfect foresight modelling, the cost saving from storage is one-third lower.
- The consideration of unpredictable changes in residual load
  - requires **reserves** to avoid lost load,
  - these reserves **limit the adaption of capacities** and
  - **waiting** reduces efficiency gains of energy storage.
- So far **social planer solution** → But how to motivate competitive storage operators to consider this strategy? Or holding public reserves?
- So far load only conditional expectations → **deterministic load + conditional expectations**


ANY
QUESTIONS
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