Optimal storage in a renewable system -

Ignoring renewable forecast is not a good idea!

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Motivation

- **Storage**: potential to increase **efficiency** of electrical systems - especially in the context of **integrating intermittent renewable technologies**.
  → load equilibration → adjustment of generation structure → efficiency
- Our previous work („*Optimal storage investment and management under uncertainty – It's costly to avoid outages!*“, IAEE Bergen, 2016) showed how differently storage operates if it faces a stochastic future rather than a known future
- But the near future is actually quite well-known…

What is the value of forecasting in a system with storage?

Optimal storage in a renewable system – Ignoring renewable forecast is not a good idea!

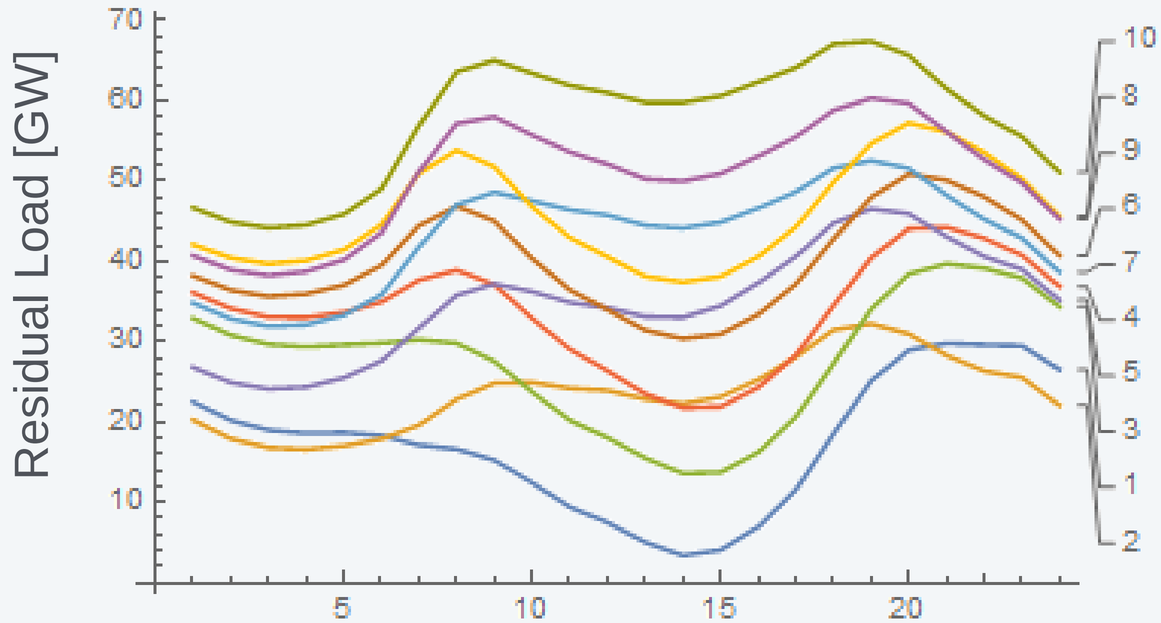
1. Information, expectation, residual load Markov process, accuracy
2. 24h-residual load pattern: definition, transition, accuracy
3. Stochastic electricity system model (SESeM-Patt) structure
   a. Electricity generation and storage operation within pattern
   b. Storage operation in-between pattern
   c. Capacity optimization
4. Results of a case study - 300 GWh storage capacity
5. Conclusion

1. What's wrong with the residual load Markov process?

- Most straightforward way of modelling residual load components: **Markov Process** estimated by hourly e.g. wind generation - perfect in the long run, **poor in the short run**!
- Problem: we know more about the future due to **forecasting**. To derive an accurate optimal storage strategy, forecasting of residual load has to be considered!
- We do not know an “off the shelf” stochastic process that resolves the problem. What to do?
    - **Additional Information:** add future process realizations as states to condition the optimal strategy. Wind: up to 100 hours/states required → infeasible!
    - **Process adjustment:** perfect knowledge for 24 hours (pattern) + Markov transitions between the patterns. Definition of a new Markov process based on 24-hour residual load vectors rather than on hourly residual load values!

2. Pattern definition and …

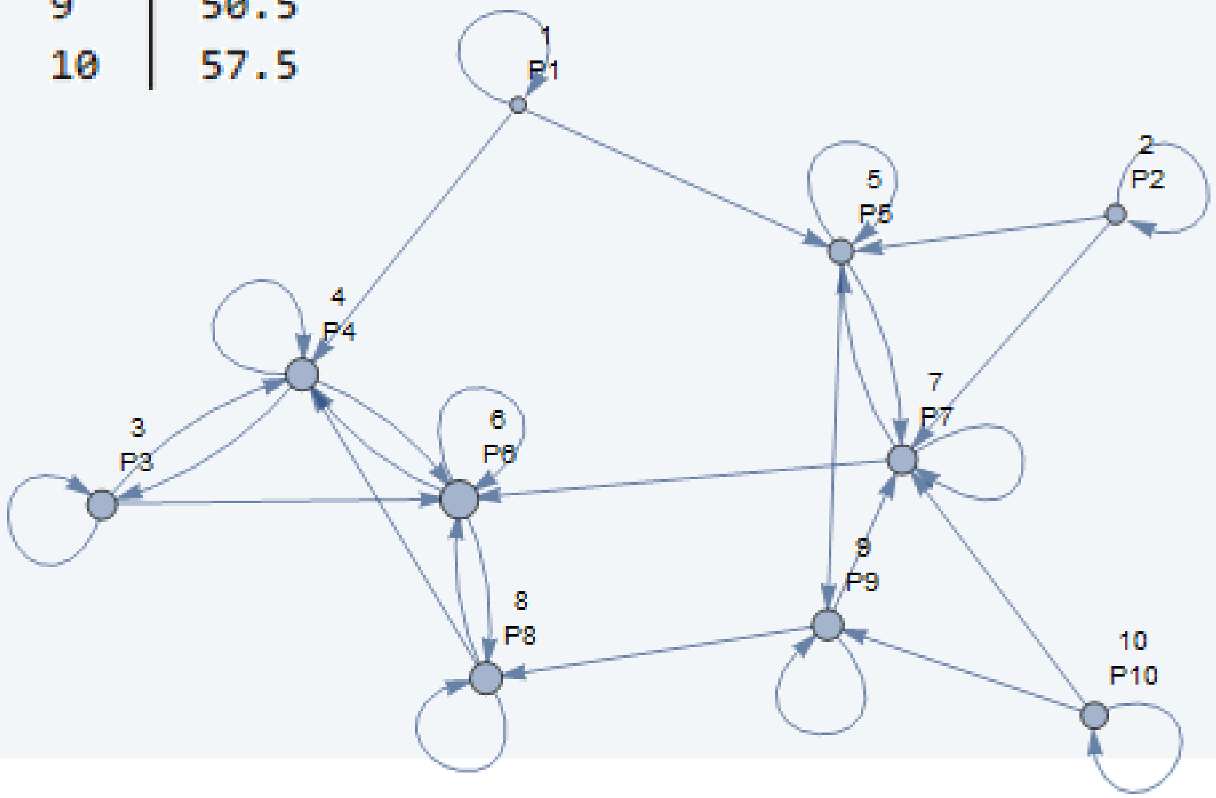
- Implementation: Residual load – composed by load factors for sun and wind scaled by 40 GW each subtracted from load – Germany 2011-2015
- Building 10 clusters and considering the 24h-cluster mean:



Cluster number

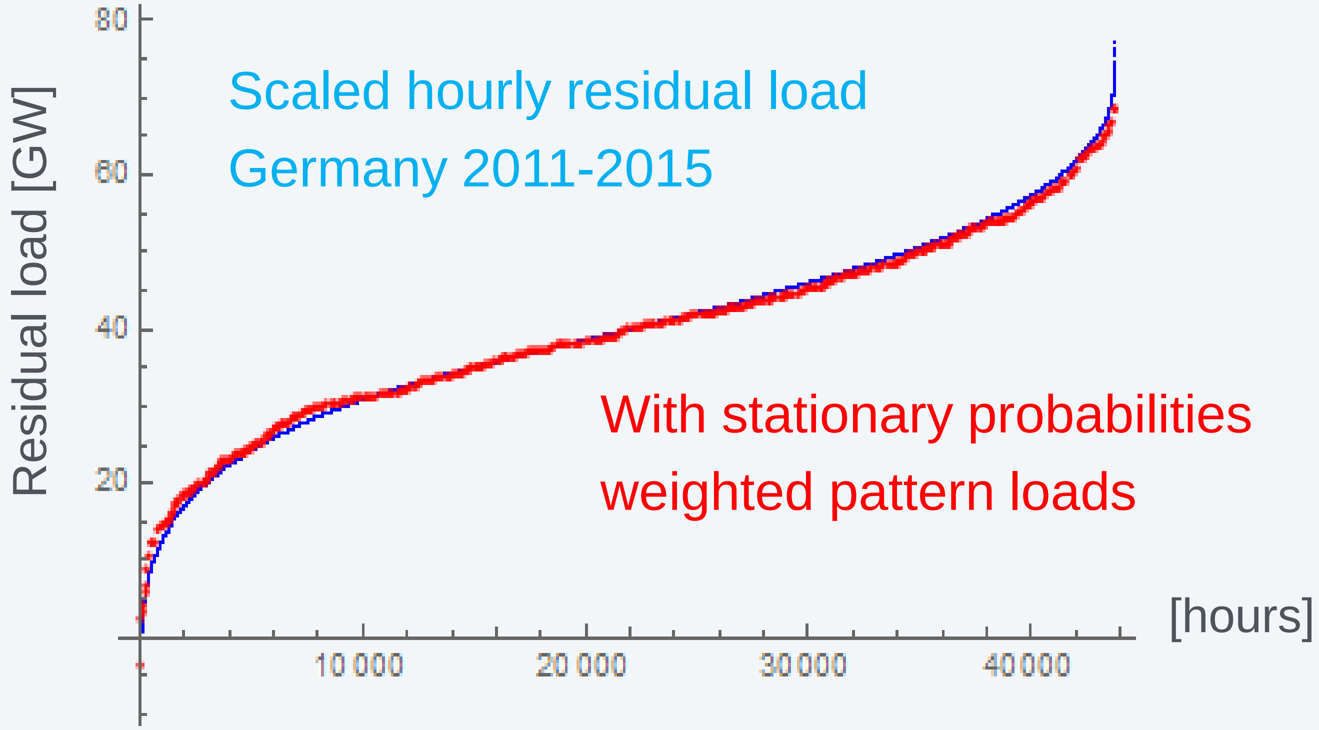
	MeanRL
1	17.3
2	23.6
3	27.6
4	33.8
5	34.9
6	40.
7	43.2
8	45.9
9	50.5
10	57.5

- Counting transitions between clusters
  → Markov Process
  → Stationary distribution

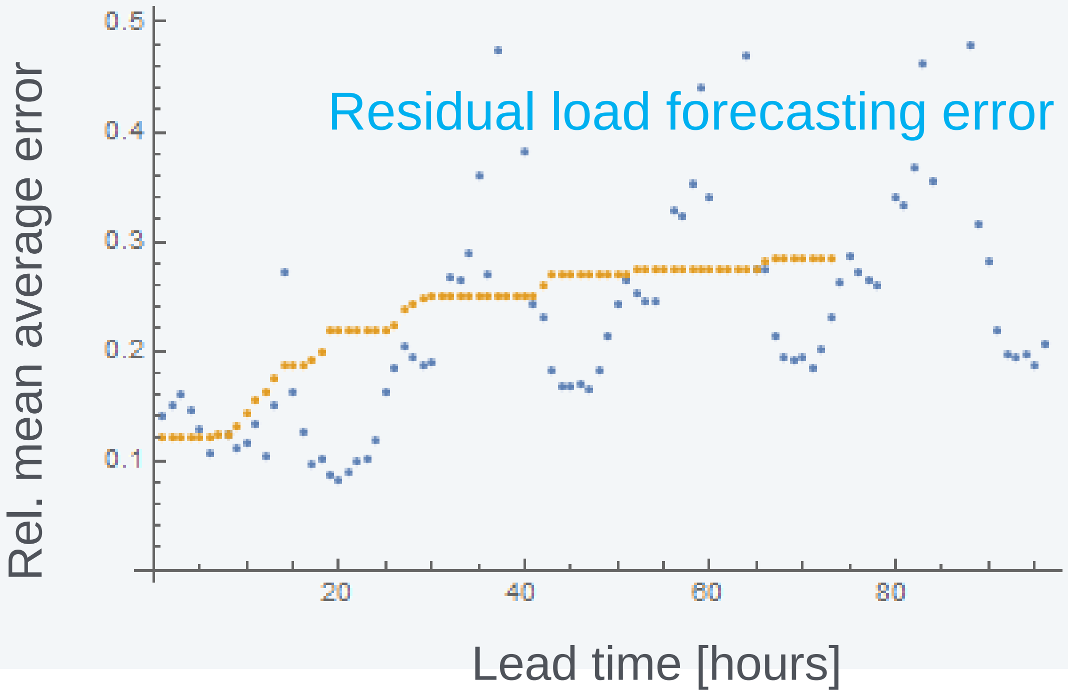


2. … accuracy

- Long term: expected residual load (pattern weighted with stationary probabilities)
- Very good!



- Short term forecasting error: mean average error of the expected vs. actual residual load by lead time
- Improved, satisfying!



3. Stochastic electricity system model

a. Electricity generation and storage operation within pattern

- Most simple 24 hour perfect foresight electricity system model
- Generation technologies with capacities k and generation g; fix and variable cost:
- Minimize 24-h operation cost over generation and storage

$C^{Var}(Pattern$ ... $\sum_{h=1}^{24} c^{var} g_h$

Technology	Variable cost	Fix cost
	€/MWh	€/KW
Nuclear	22.5	3250
IGCC	25	2500
Coal	27	2000
Combined Cycle	40	800
Cobust Turb.	55	650
Lost Load	5500	0

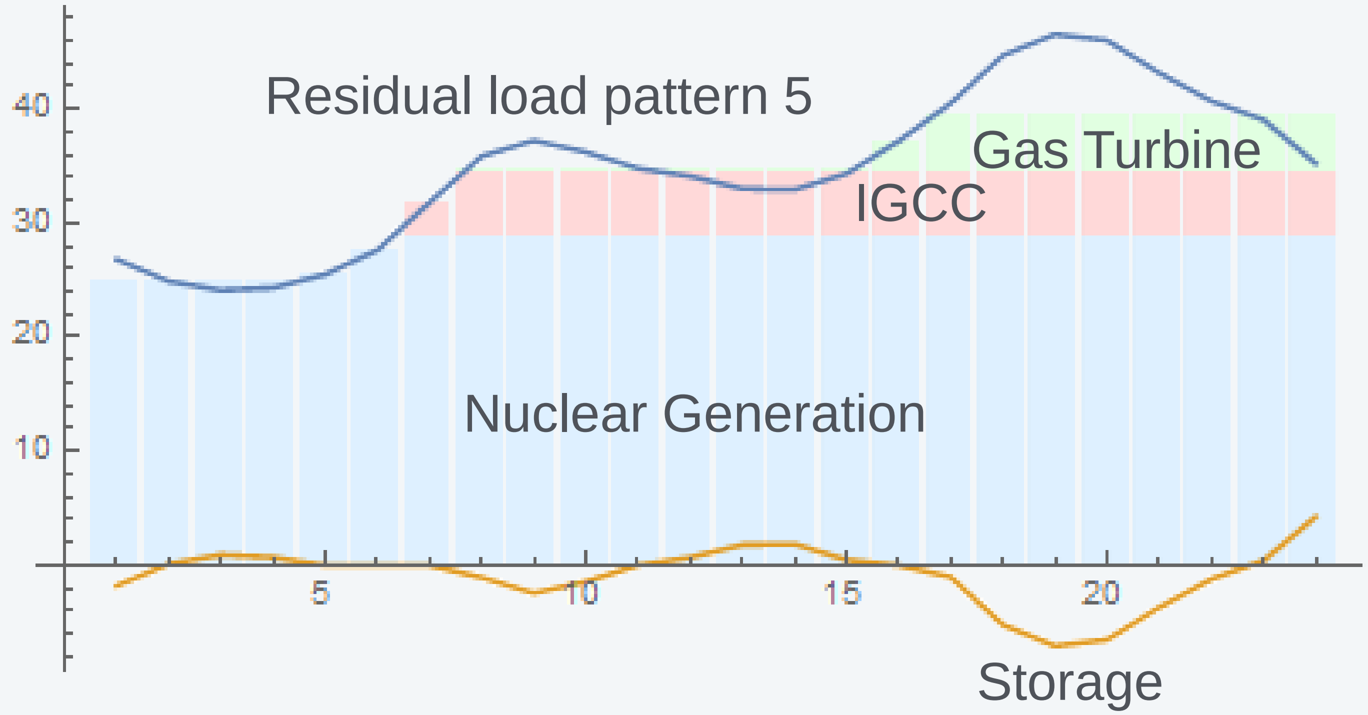
- Restrictions:
  - generatio
  - Residual
  - SOCIn giv
  - Storage c

3. Stochastic electricity system model

a. Electricity generation and storage operation within pattern

Example:

- Pattern 5, State of charge 30GWh
- Action net storage +10 GWh at 24.00
- Example: Capacities $\{29.01, 5.53, 9.554, 13.359, 0, 12.5\}$



→ Variable cost for every **pattern-StateOfCharge-storage** combination

3. Stochastic electricity system model

b. Storage operation in-between pattern

- Now: determination of the best action (storage) – still given capacities
- It can be shown that operation cost minimization by inter-pattern storage (Markov decision process) is equivalent to a “minimum cost flow” problem

→ Solution as linear program

→ Optimal storage action in each state!

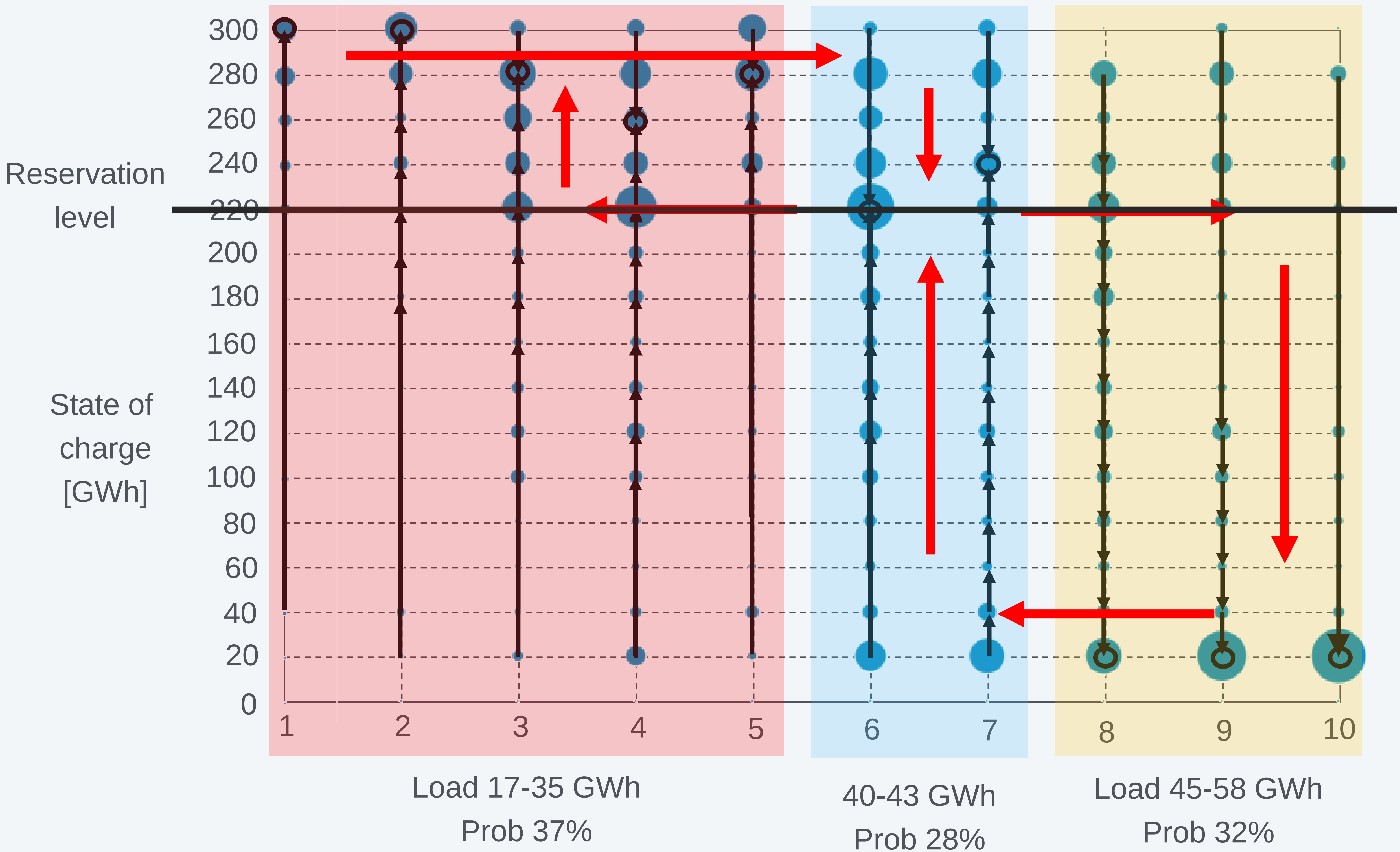
→ Total 24h expected operation cost → extrapolation to 40 years total operation cost

c. Capacity optimization

- **Capacity optimization:** minimize fix cost + 40 years operational cost!
- It is considered that each change in capacities induces changes in intra-pattern storage and generation and inter-pattern storage
- We are able to solve this problem numerically in a case study for 300GWh storage

4. Results

Optimal inter-pattern storage



4. Results

Optimal system structure – depending on forecasting

Information and Storage Scenario	24h-Pattern		
	Without storage	300 GWh intra pattern st	300 GWh intra+inter pattern st
Generation capacities [GW]			
Nuclear	27	26	29
IGCC	6	8	5
Coal	13	11	9
CCGT	15	12	13
Comb. Turbine	5	0	0
Lost Load	0	0	12
Total	67	58	57
Total cost [Mio €]	487350	475806	472699
	Basis	-2.3%	-3%

Length of perfect forecasting window [h]

5. Conclusion

- We developed a **stochastic multi scale model** of the electricity system (from hourly basis to a 40 year lifespan)
- Capable of information modelling (**forecasting**), deviation of generation & storage decisions (**operation**) and capacity optimization (**investment**)
- Even though a lot is known about the near future there is still uncertainty.
  → **Waiting and reservation** levels in the storage to reduce the negative impact of „bad“ events, but reducing the potential in „good“ cases
- In a numerical **case study** with 300 GWh storage option
  - With 24-hour pattern 76% of the efficiency gain by storage could be realized compared to perfect foresight
  - Without any forecasting the efficiency gain dropped to 30%
  - 18% of the efficiency gain in the 24-hour pattern was related to inter-pattern storage
- Inter-pattern storage requires reservation levels. Might be **difficult to implement** via competitive storage operators


ANY
QUESTIONS
?

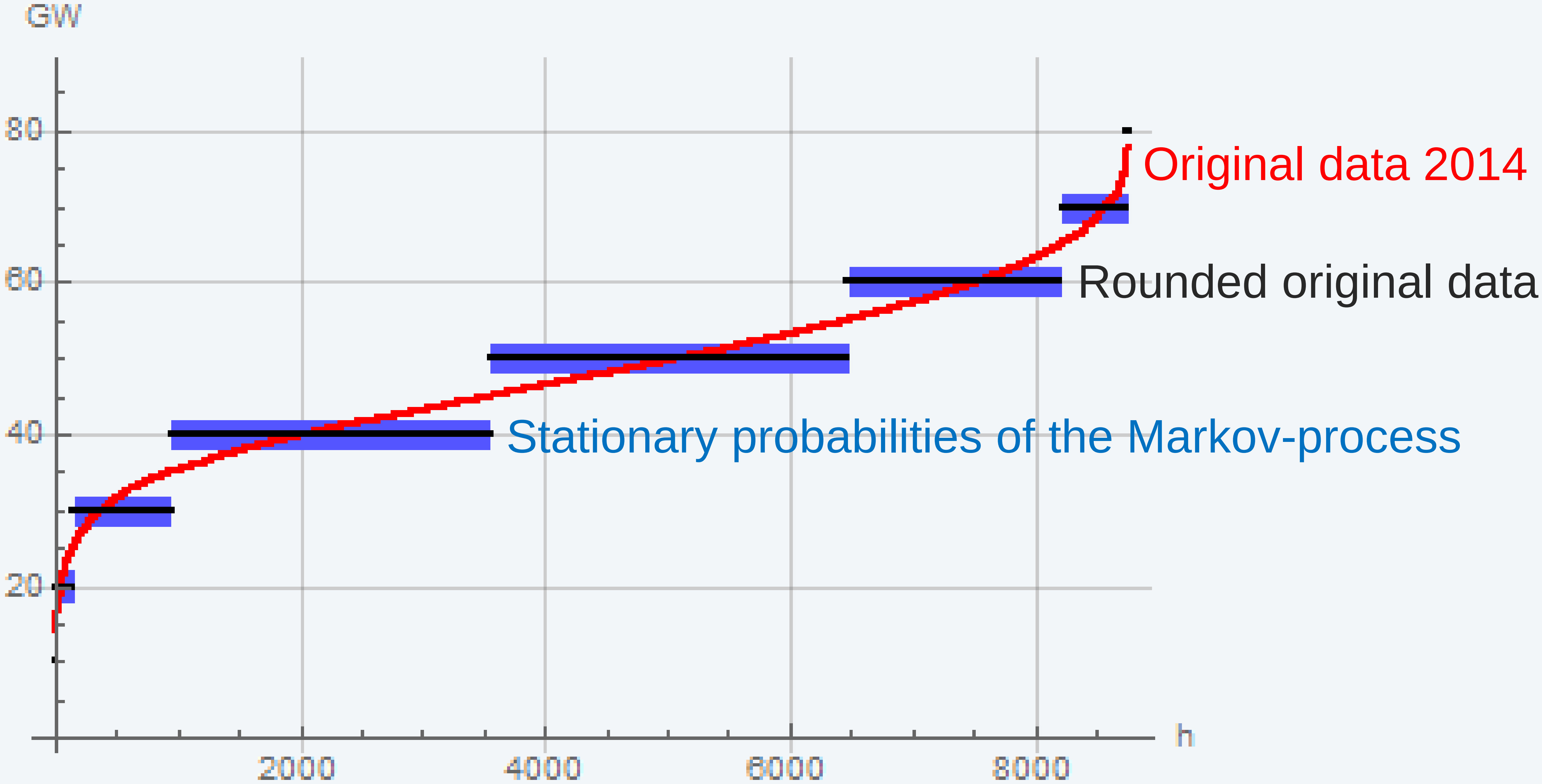
Transition matrix

	MeanRL	Probs	1	2	3	4	5	6	7	8	9	10
1	17.3	0.03	0.17	0.09	0.13	0.2	0.17	0.13	0.04	0.	0.07	0.
2	23.6	0.05	0.12	0.44	0.02	0.01	0.28	0.	0.12	0.	0.01	0.
3	27.6	0.11	0.09	0.02	0.26	0.18	0.08	0.21	0.05	0.09	0.02	0.01
4	33.8	0.13	0.05	0.03	0.3	0.19	0.05	0.22	0.05	0.07	0.03	0.
5	34.9	0.07	0.	0.13	0.04	0.04	0.24	0.06	0.17	0.08	0.17	0.07
6	40.	0.19	0.01	0.	0.13	0.25	0.04	0.32	0.05	0.13	0.05	0.01
7	43.2	0.1	0.01	0.06	0.03	0.06	0.15	0.14	0.25	0.09	0.14	0.07
8	45.9	0.13	0.	0.	0.03	0.14	0.	0.31	0.03	0.39	0.06	0.04
9	50.5	0.11	0.	0.	0.02	0.04	0.01	0.12	0.17	0.16	0.33	0.14
10	57.5	0.08	0.	0.	0.	0.	0.01	0.01	0.11	0.03	0.27	0.57

1. Representation of residual load uncertainty

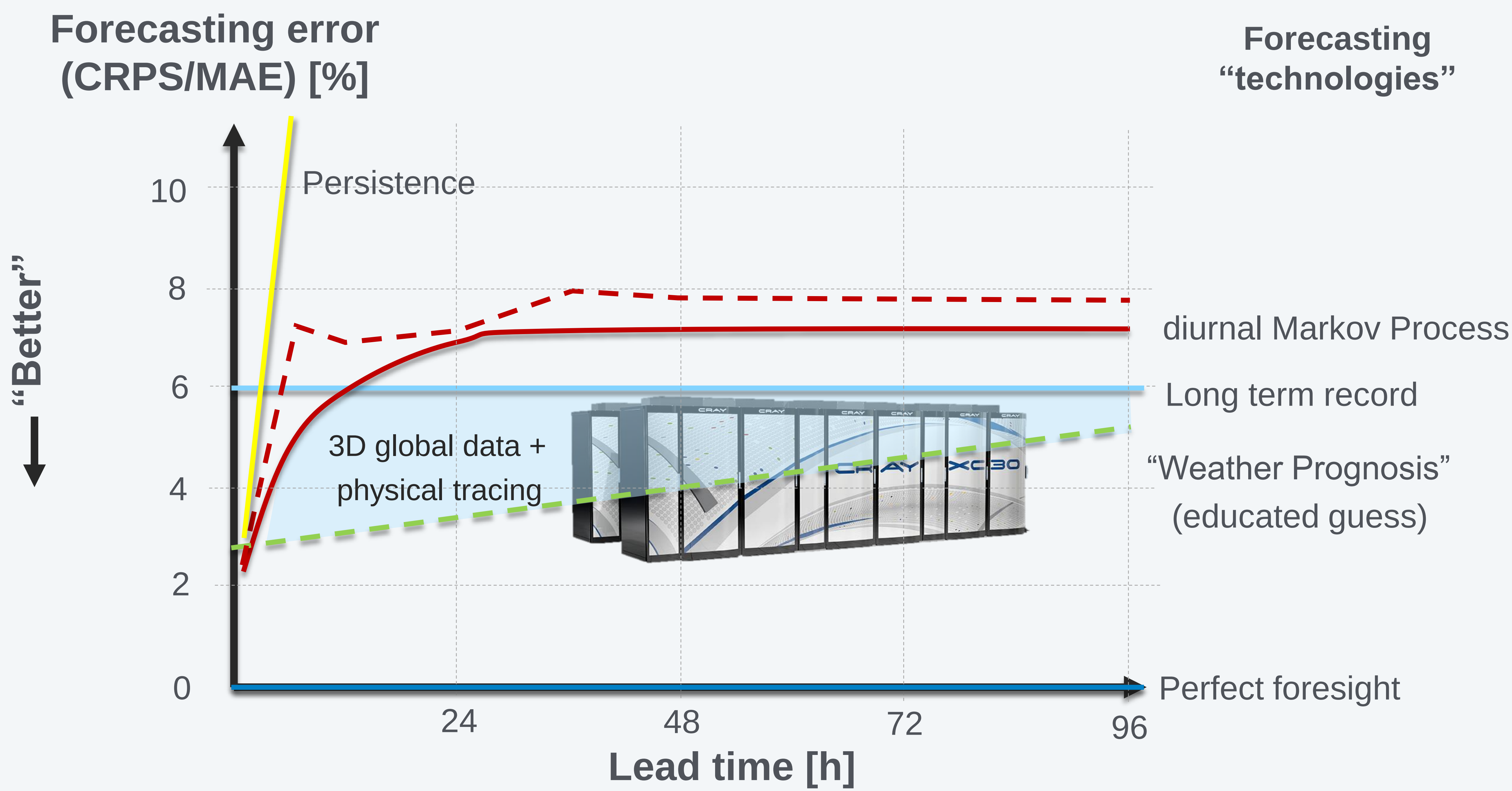
Load duration curve

- Residual load of Germany 2014



→ almost perfect fit

1. Representation of residual load uncertainty



3. Model – inbetween pattern

Model

- Most simple stochastic electricity system model

$$\min_{k,\pi} c^{fix} k + \mu_{Sto} \lim_{T\to\infty} \frac{1}{T+1} E[C^{Var}(Pattern, SOCIn, \Delta SOC | k)]$$

- Solution: Decision rule π (strategy) for every pattern to exploit new information about the next pattern to come!
- Numerical solution of a series of Markov Decision Problems (MDP) for strategy and stationary probabilities | capacities
- Case: 300 GWh storage option, 20 GWh steps.
- Select the change in SOC given according cost and transition probabilities between pattern.

Daten Kosten, Scenario – Erneuerbare Kapazitäten

Algorithmus

Results: Storage Strategy

	$P1-5$	$P6-7$	$P8-10$
$P1-5$	0.66	0.21	0.12
$P6-7$	0.37	0.38	0.26
$P8-10$	0.09	0.25	0.66

Residual load uncertainty