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The bubbles contain my comments on the presentation, which can be viewed by moving the mouse over them

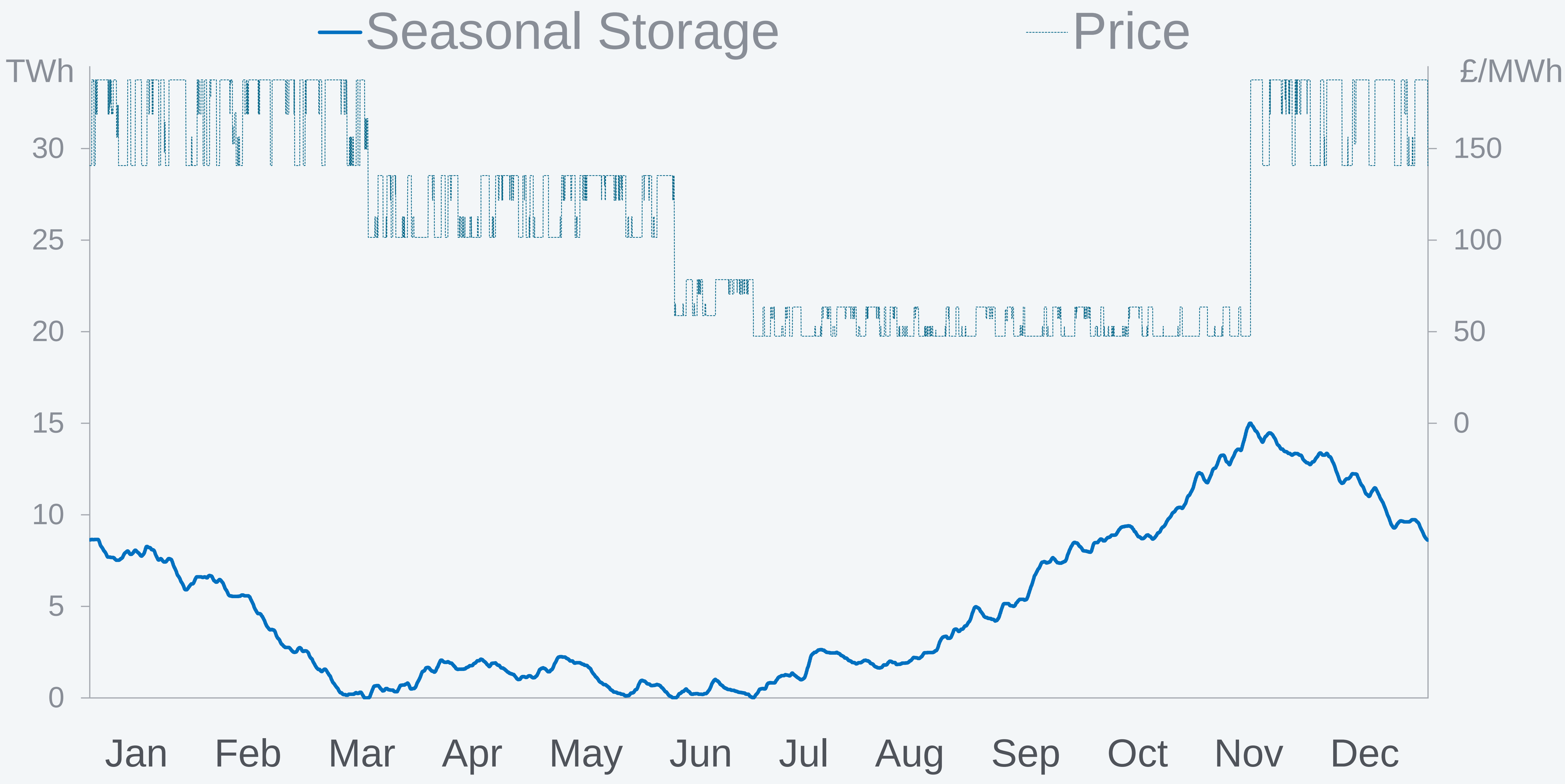
Optimal Storage, Investment & Management under Uncertainty – It is costly to avoid outages!

Joachim Geske and Richard Green

Mathematics of Energy Systems,
Isaac Newton Institute, 18 March 2019

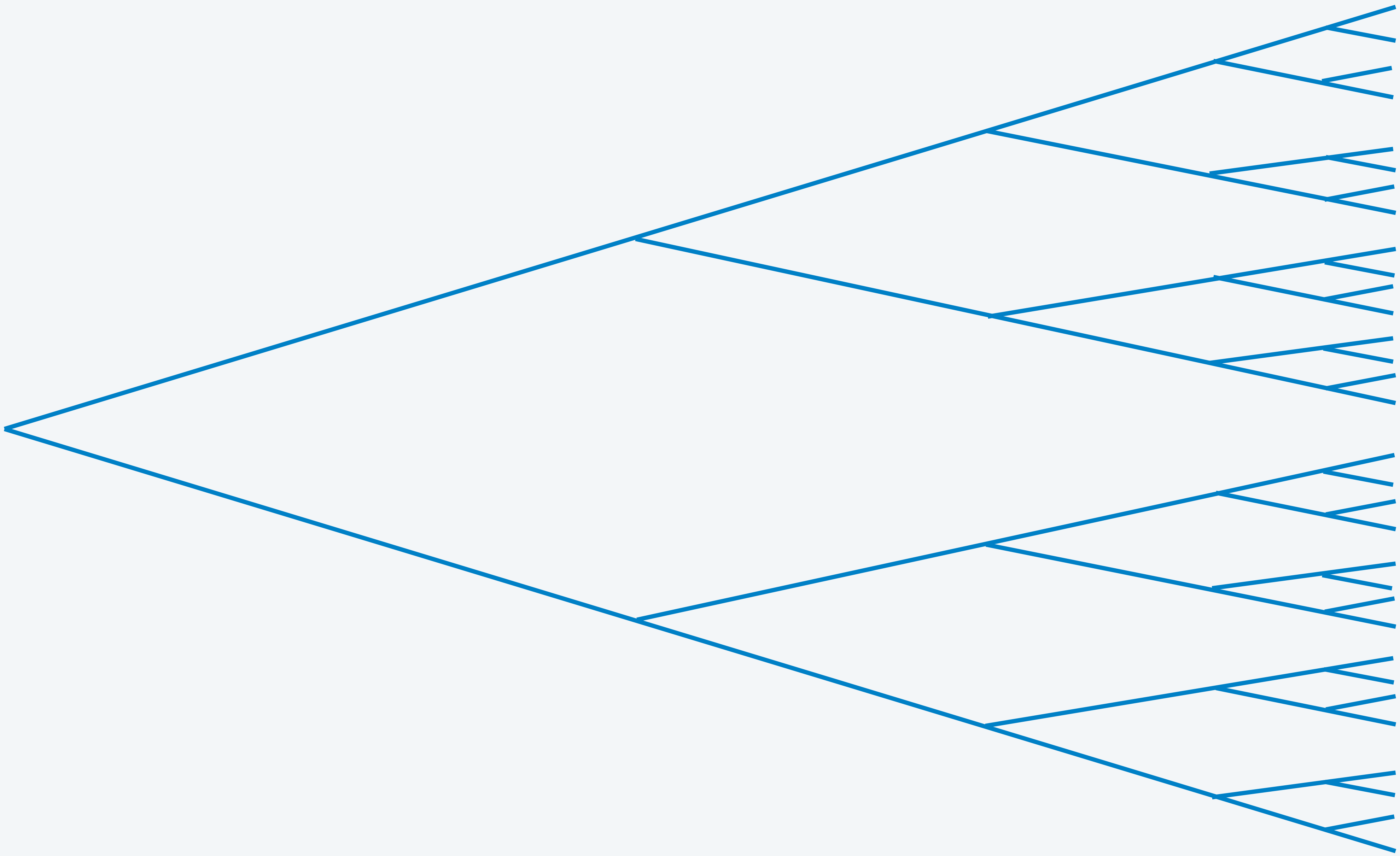
How to model uncertainty

The easy way



How to model uncertainty

The intensive way



How to model uncertainty

A stochastic way

- Markov Chain representation of load
- Storage as a second state variable
- Optimal operation is a Linear Programme
- Optimal capacities from Load-duration curve

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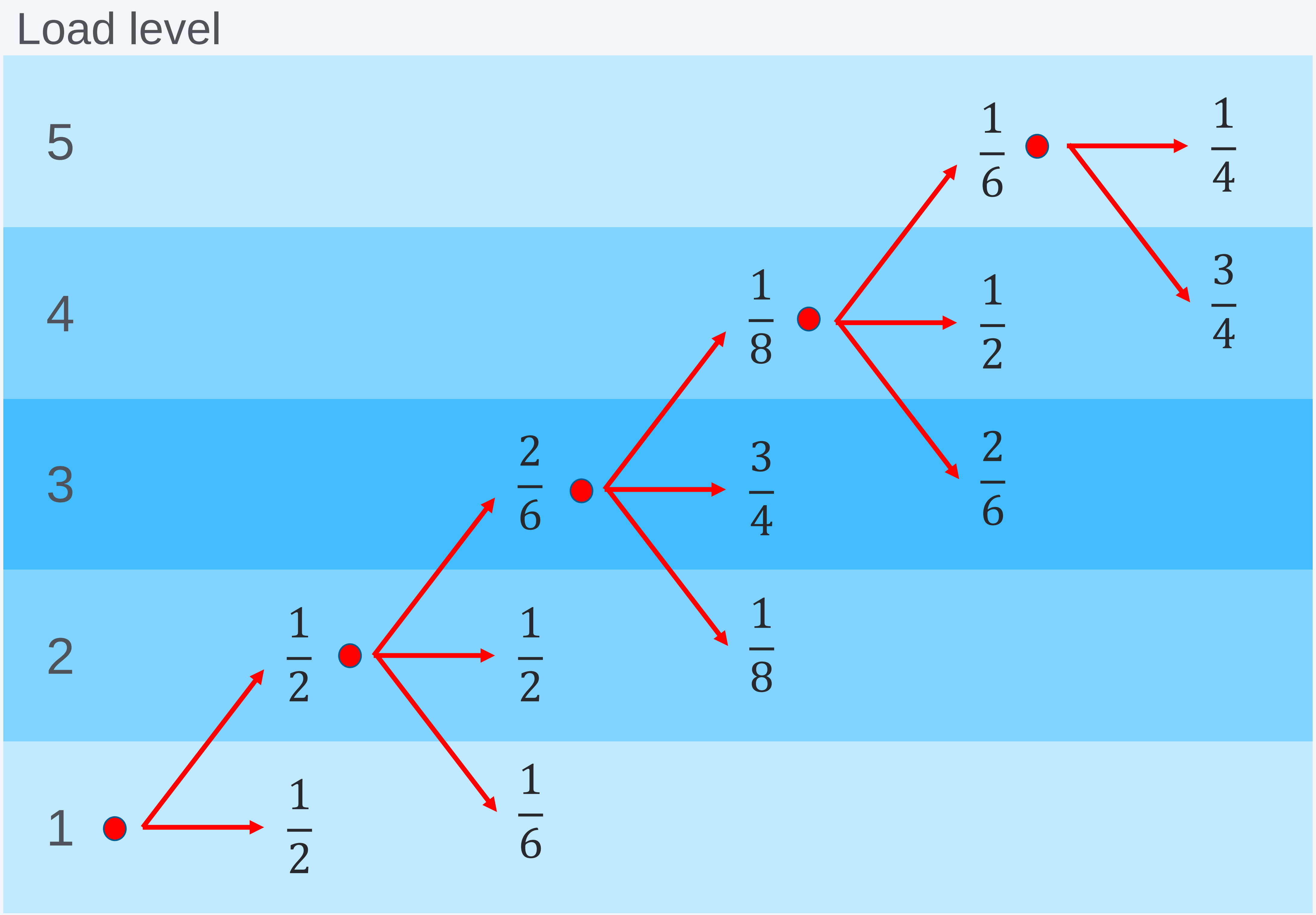
A small-scale model

Load as a Markov Chain

Transition probabilities between states



Load as a Markov Chain

Mathematical representation

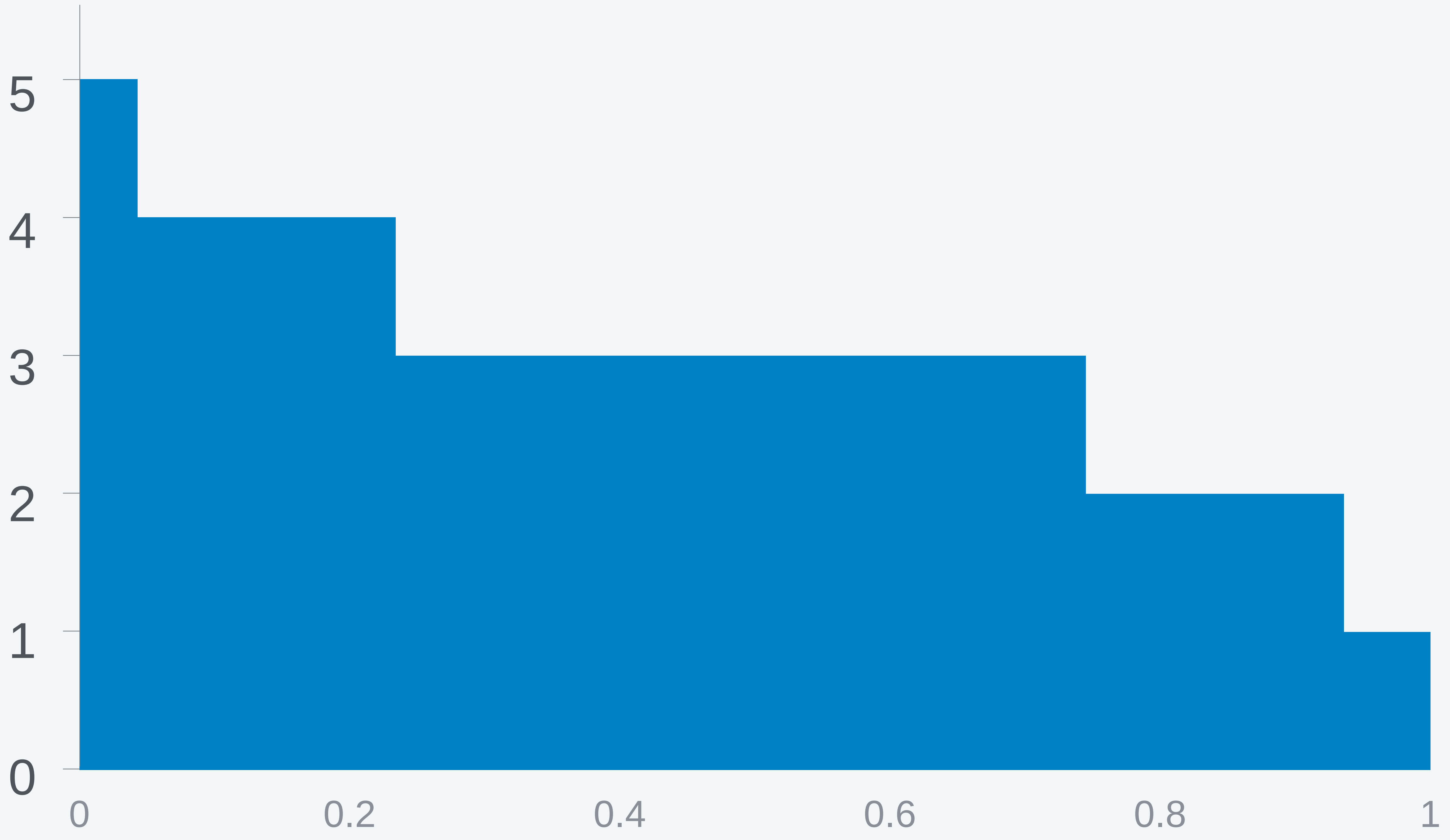
Transition matrix *P* gives probability of each state given the previous state,

$$\text{Prob}\left(D_i \middle| D_j\right) = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 \\ \frac{1}{6} & \frac{1}{2} & \frac{2}{6} & 0 & 0 \\ 0 & \frac{1}{8} & \frac{3}{4} & \frac{1}{8} & 0 \\ 0 & 0 & \frac{2}{6} & \frac{1}{2} & \frac{1}{6} \\ 0 & 0 & 0 & \frac{3}{4} & \frac{1}{4} \end{pmatrix} \qquad p^{*T} = \begin{pmatrix} 0.064 \\ 0.192 \\ 0.515 \\ 0.192 \\ 0.043 \end{pmatrix}$$

Steady-state distribution p^*, given by $p^* = p^* \cdot P$

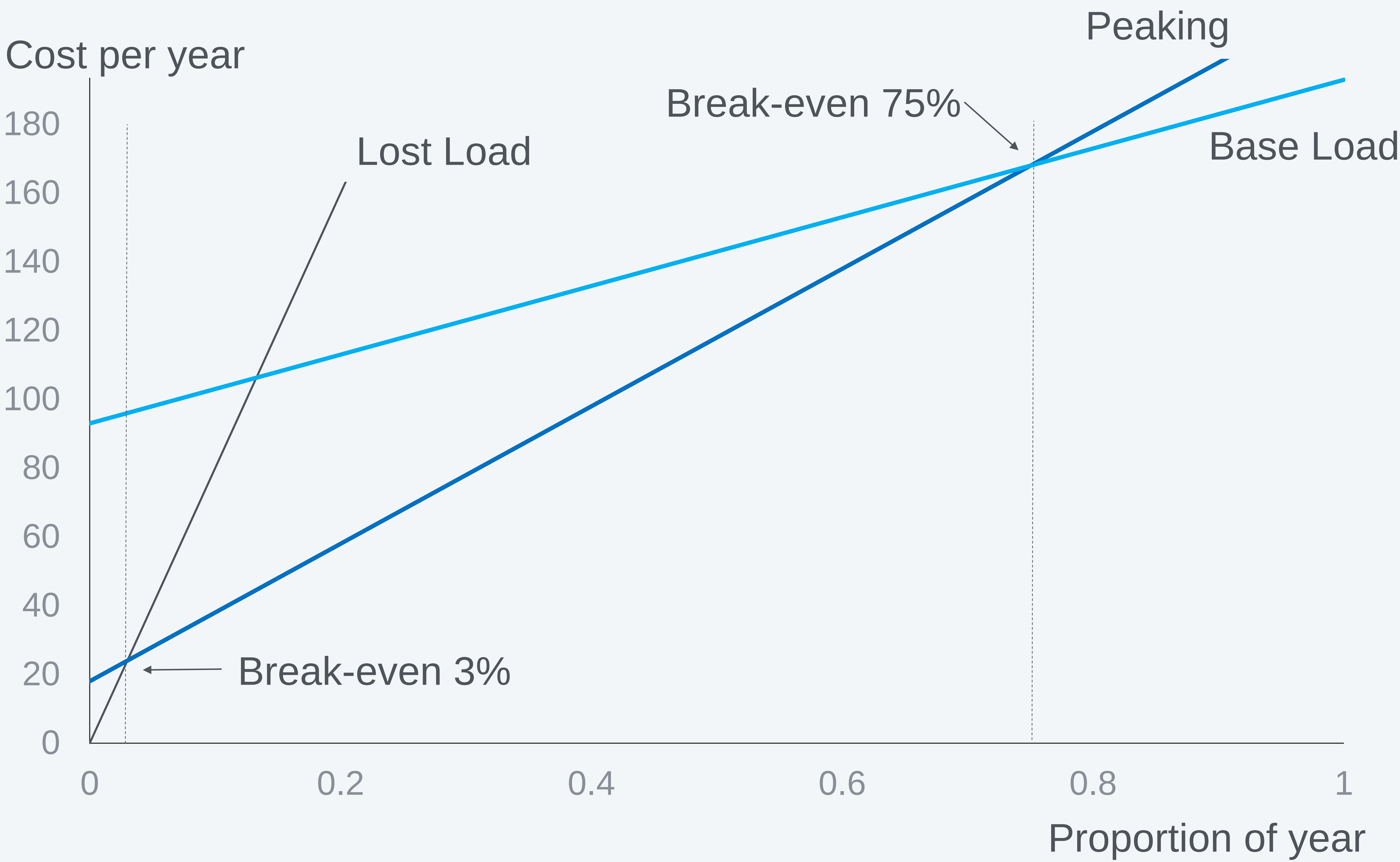
Load-duration Curve

No storage



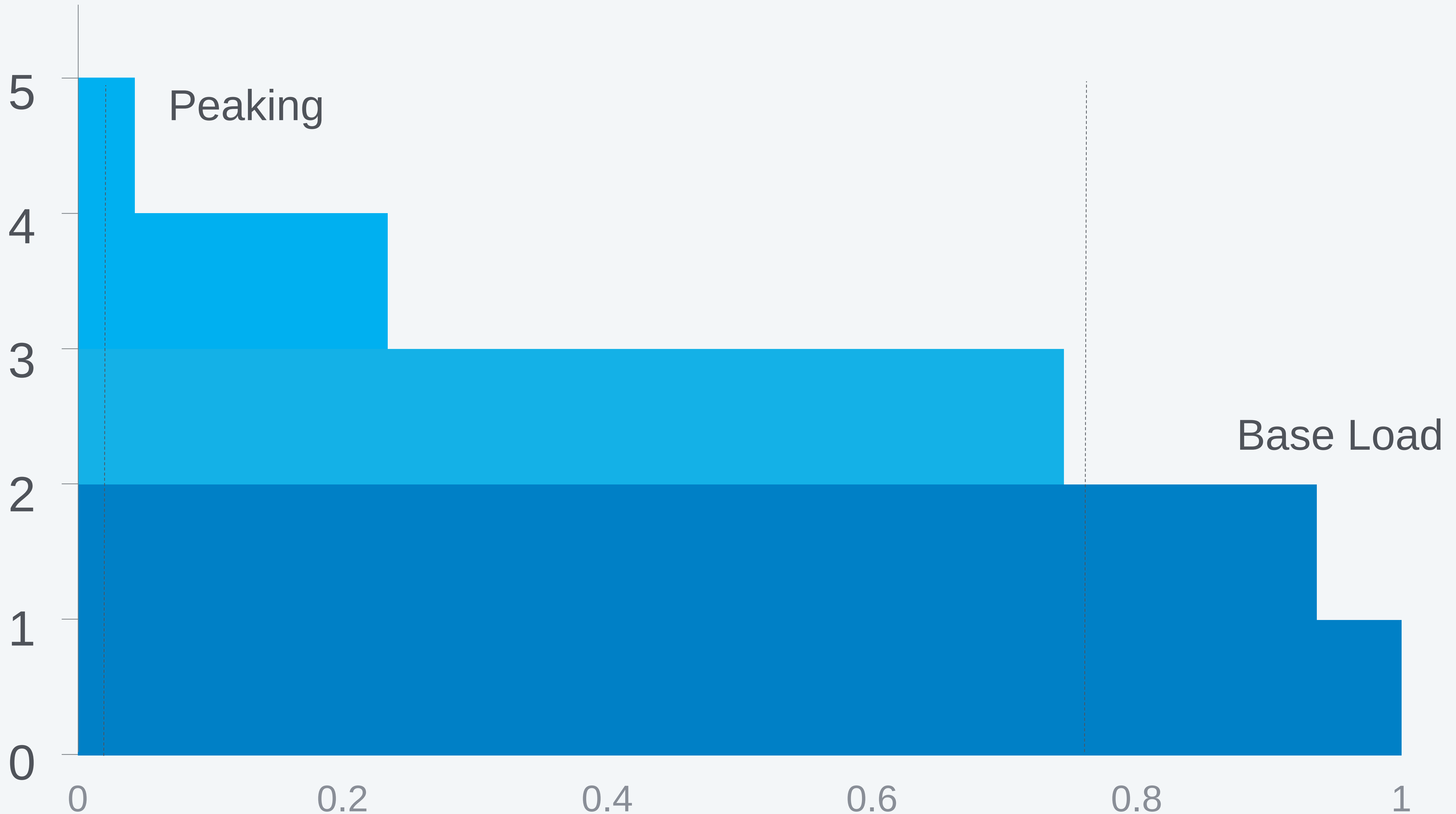
The screening curve

Fixed and variable costs

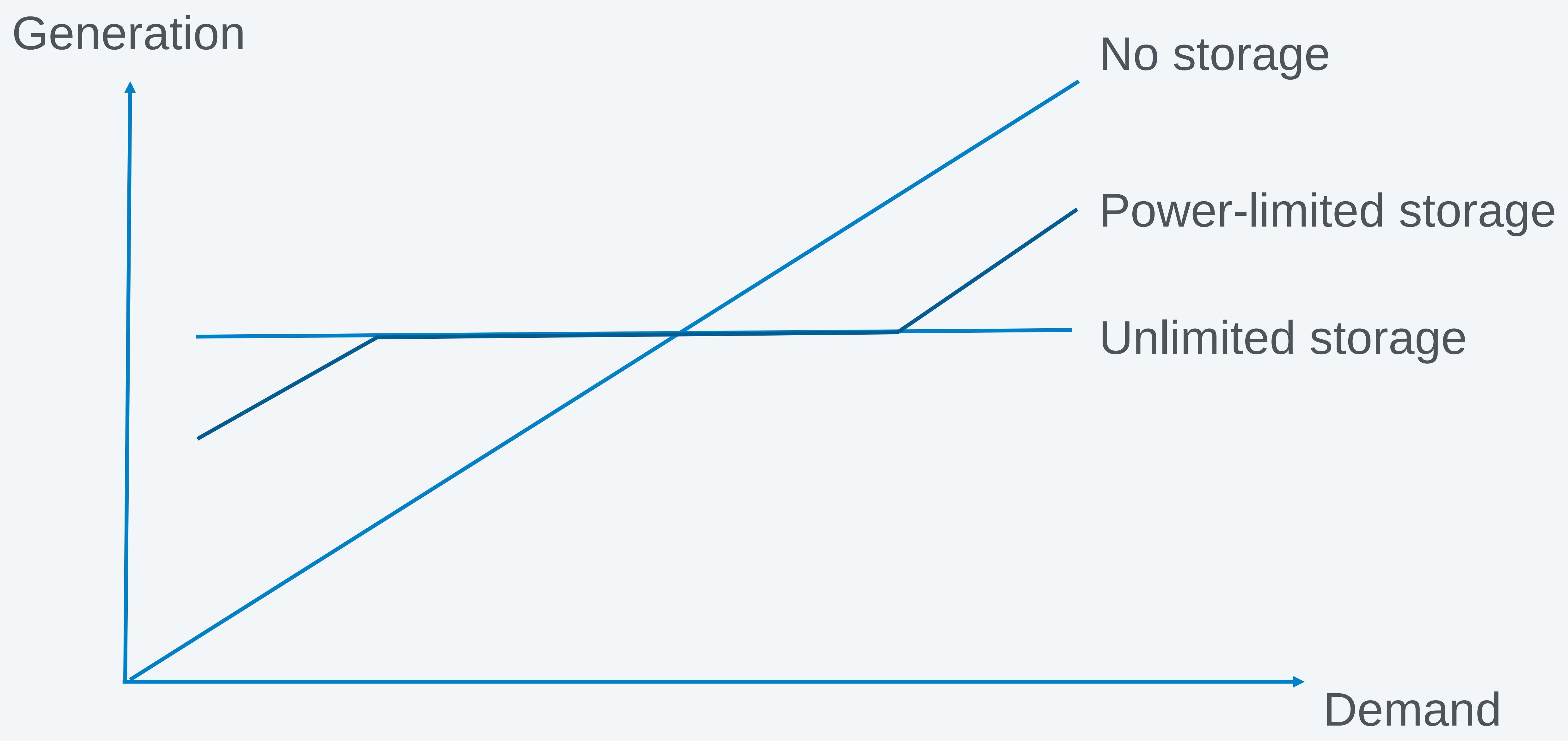


Load-duration Curve

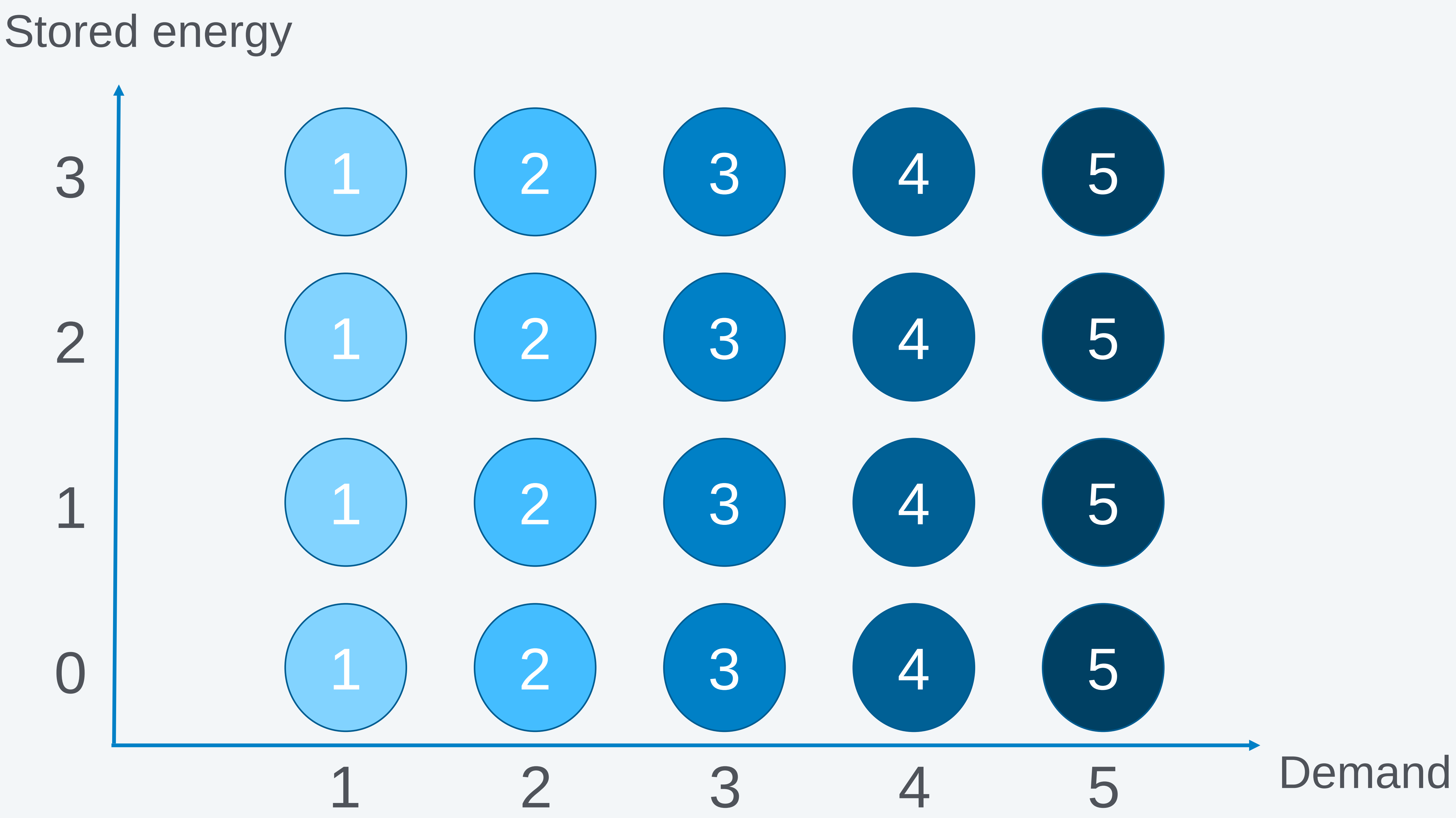
No storage



Demand, generation and storage

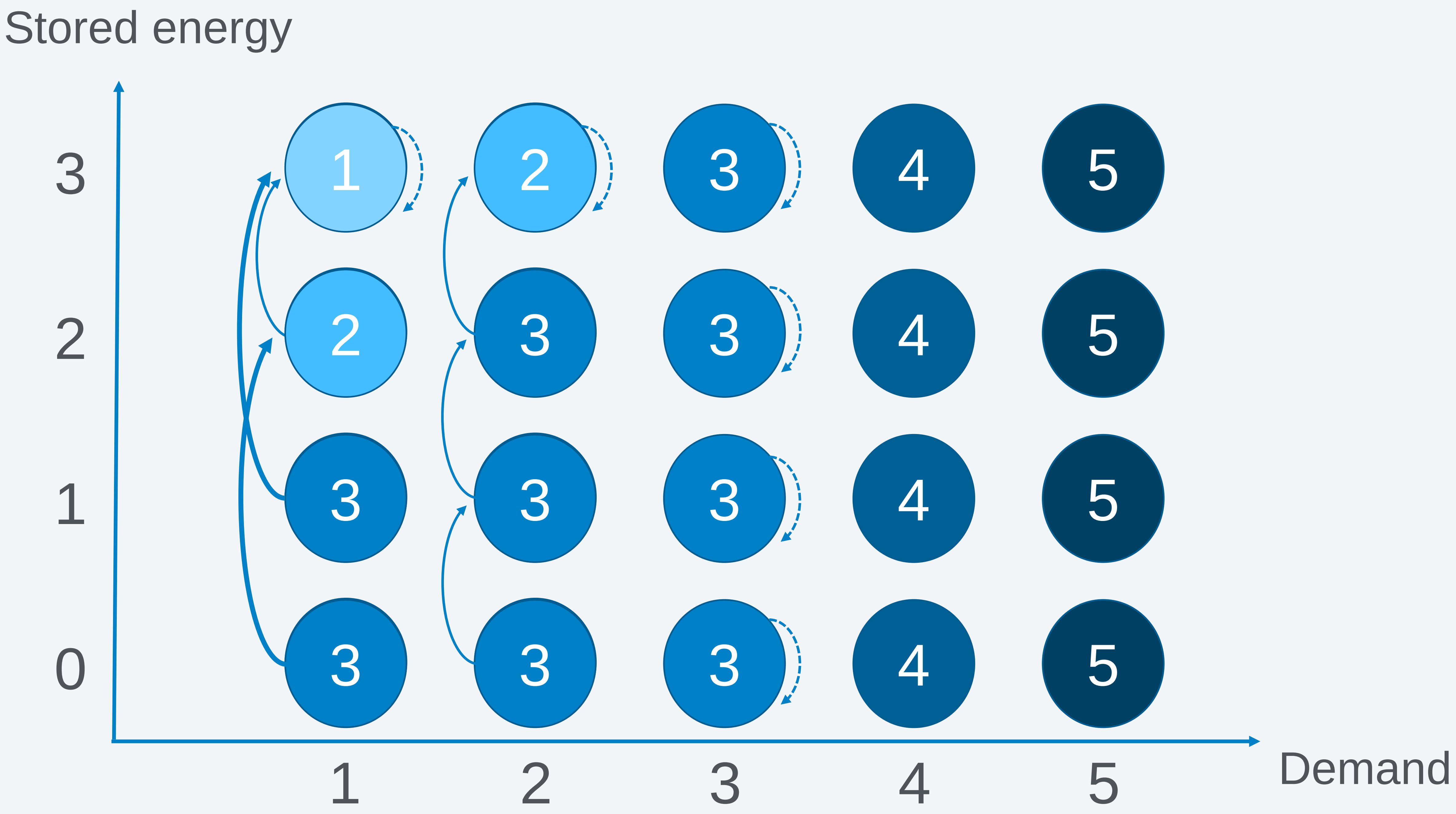


Generate to meet demand



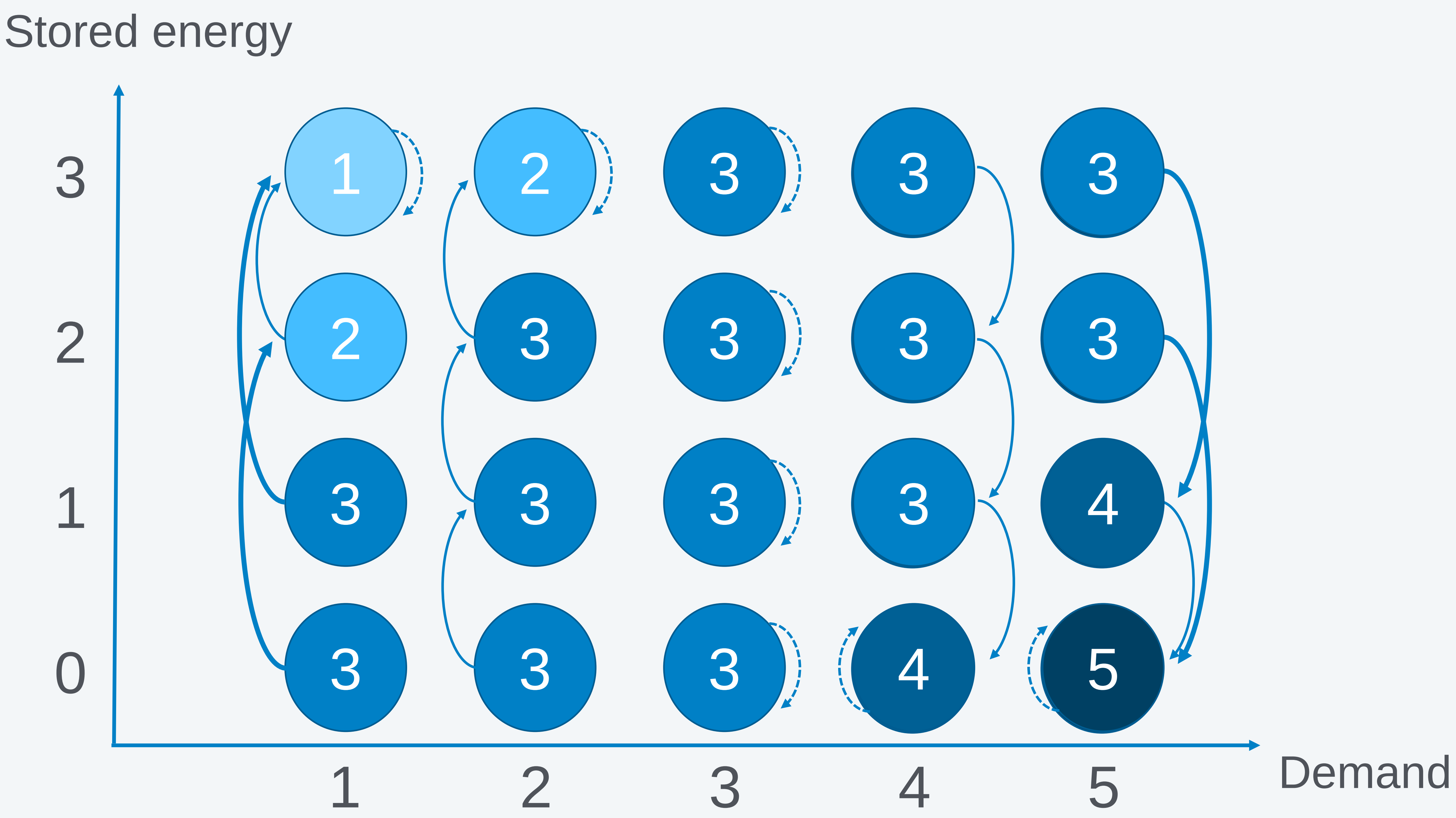
Charge storage when demand is low

The "pure arbitrage" strategy



Discharge storage when demand is high

The “pure arbitrage” strategy



Load and Storage as a Markov Chain

Mathematical representation

State now consists of demand, D, and storage level, S

s is change in storage

$A(S, D)$ is admissible set of changes:

$\{0 \leq S + s \leq$ fully charged, $D + s \leq$ generating capacity$\}$

Strategy is a distribution over $s \in A$ for each state (S, D)

Load and Storage as a Markov Chain

Mathematical representation

d((*S*, *D*), *s*) is the probability of each state-action pair:

Standard adding-up conditions

$$\sum_{(S,D),s\in A(S,D)} d\big((S,D),s\big) = 1 \qquad d\big((S,D),s\big) \geq 0$$

Σ "inflow" states = Σ "outflow" states

$$\sum_{s\in A(S,D)} d\big((S,D),s\big) = \sum_{S',D',s\in A(S',D')} d\big((S',D'),s\big)\cdot Prob\big((S',D'),(S,D),s\big)$$

$$Prob\big((S',D'),(S,D),s\big) = \begin{Bmatrix} P(D'|D) & S' = s + S \\ 0 & otherwise \end{Bmatrix}$$

Objective Function

For the operating stage, with fixed capacities

Objective is to minimise expected operating cost:

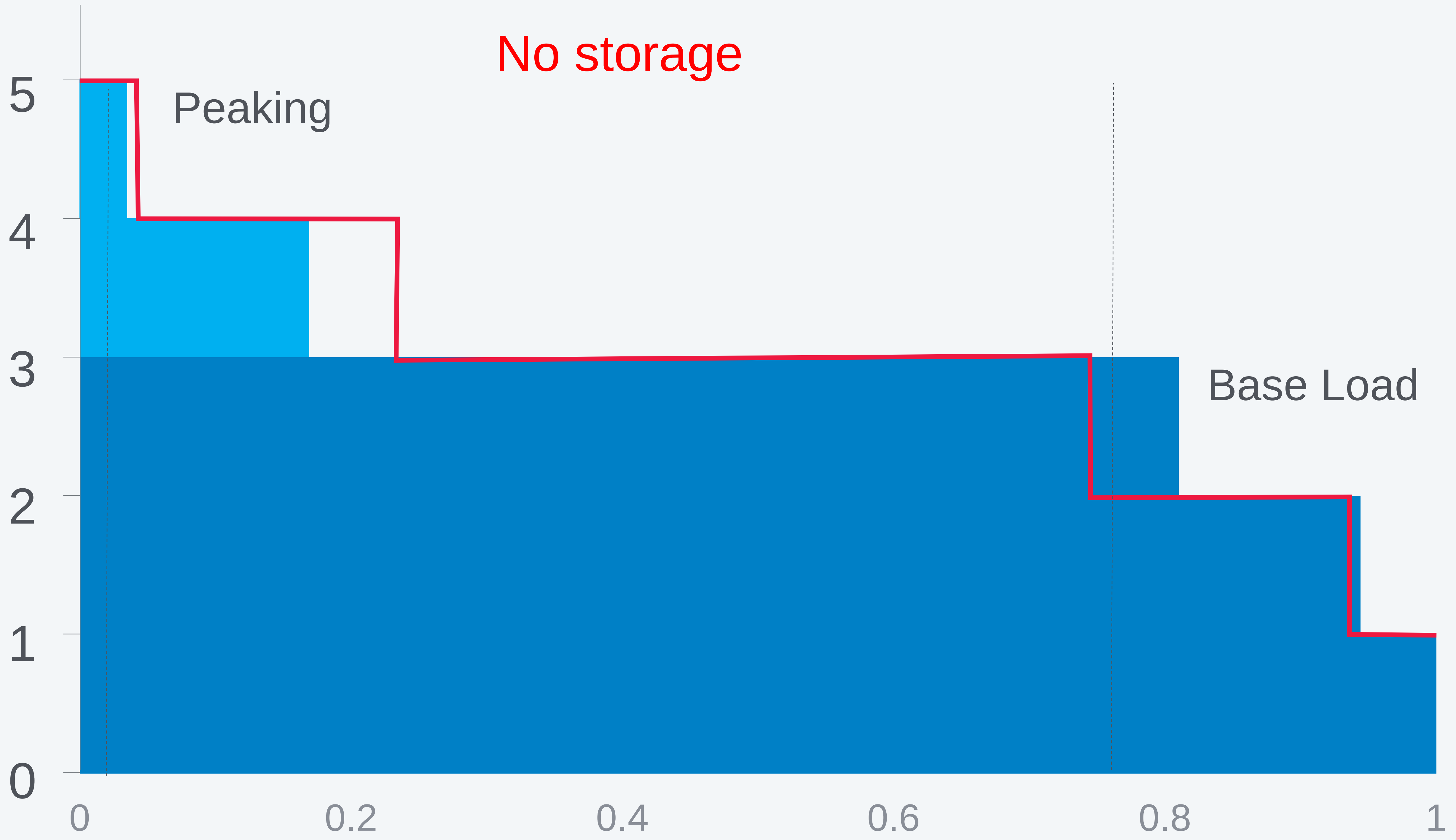
$$\min_{d((S,D),s)} \sum_{(S,D),s \in A(S,D)} d\big((S,D),s\big) \cdot Cost(D+s)$$

Decision rule for storage:

$$Prob(s|(S,D)) = \frac{d\big((S,D),s\big)}{\sum_{s' \in A(S,D)} d\big((S,D),s'\big)}$$

Load-duration Curve

"Pure arbitrage" strategy for storage



What if there's less capacity?

Algorithm for optimal capacity and operations

We are now minimising both variable and fixed costs

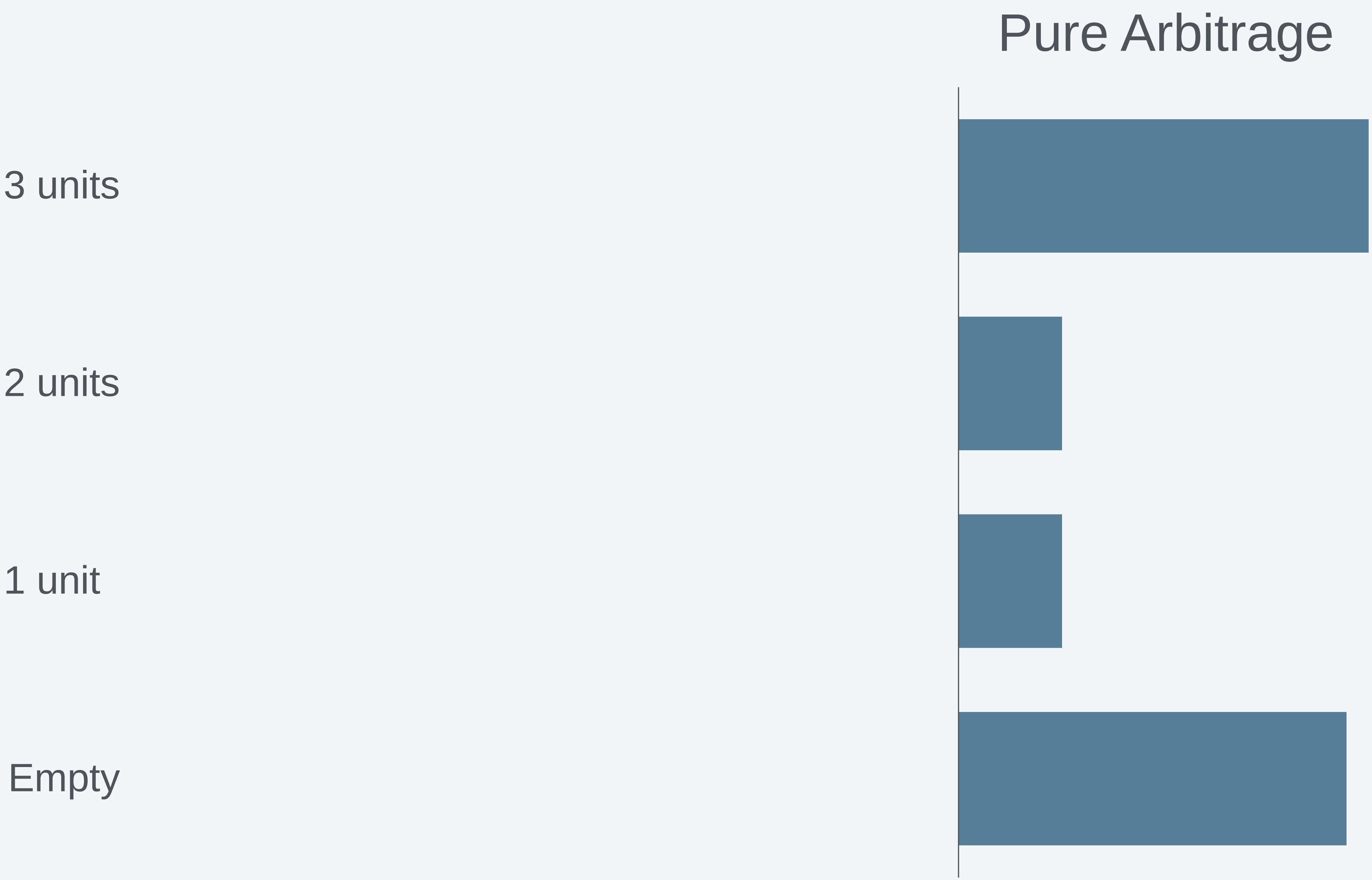
Start with no-storage Load Duration Curve (LDC) and choose optimal capacities from screening curve

Optimise storage operation, given capacities

Calculate new LDC and check if capacities are optimal

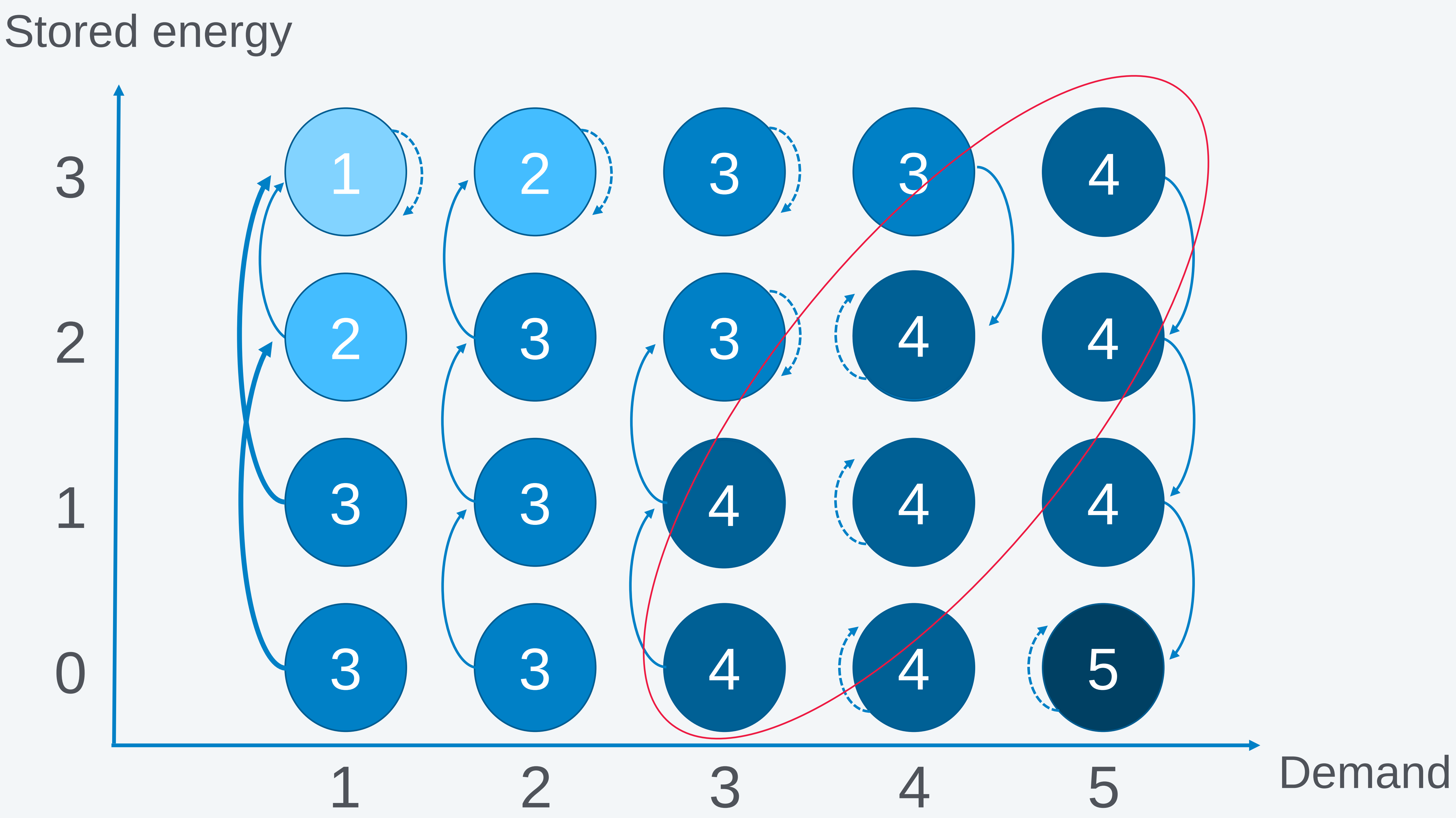
- If not, adjust capacities
- If apparently optimal, substitute small amounts of each type for its screening-curve neighbour and check for possible cost savings

Distribution of storage states



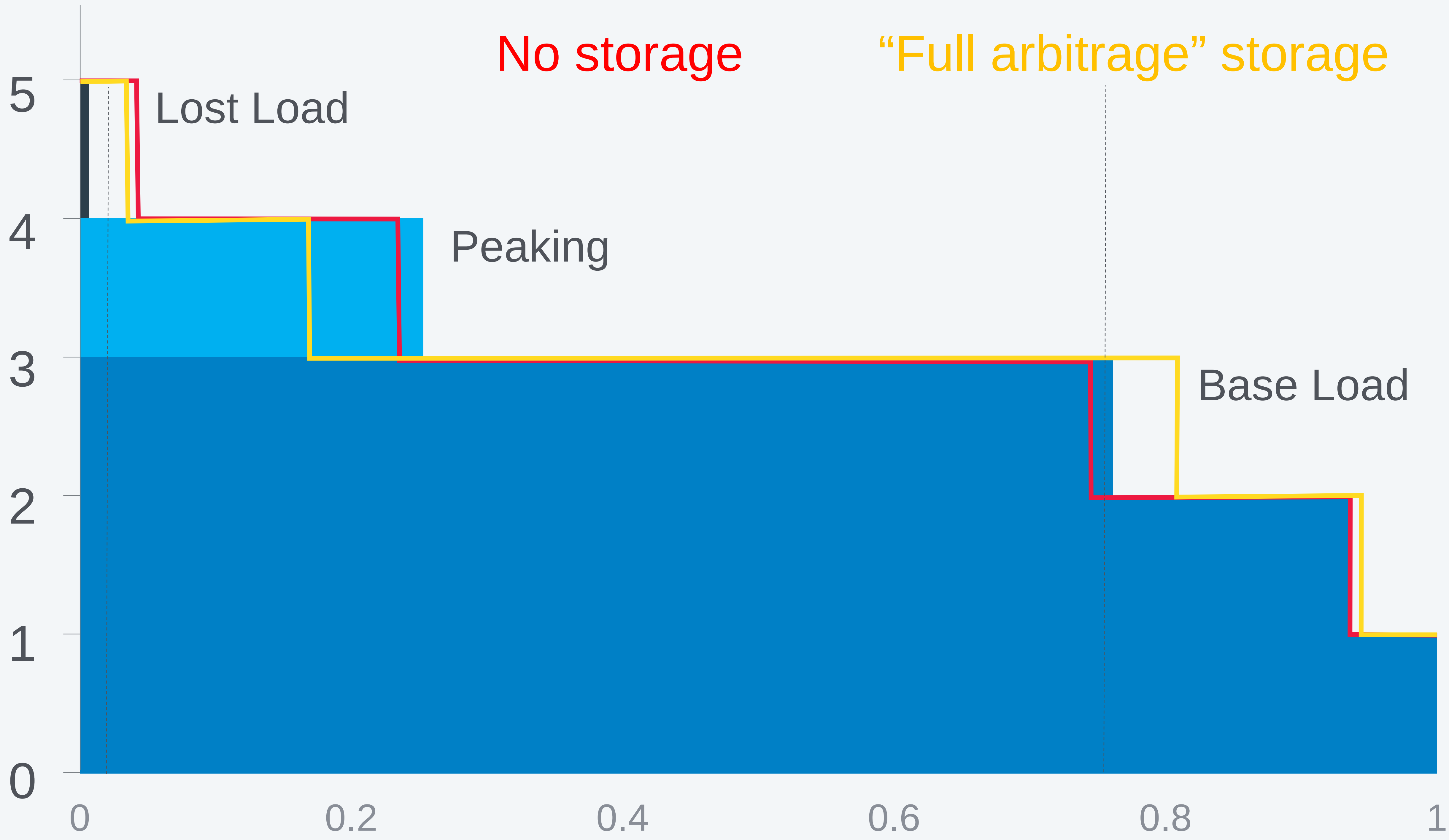
Discharge less if demand is high and storage low

The “precautionary storage” strategy

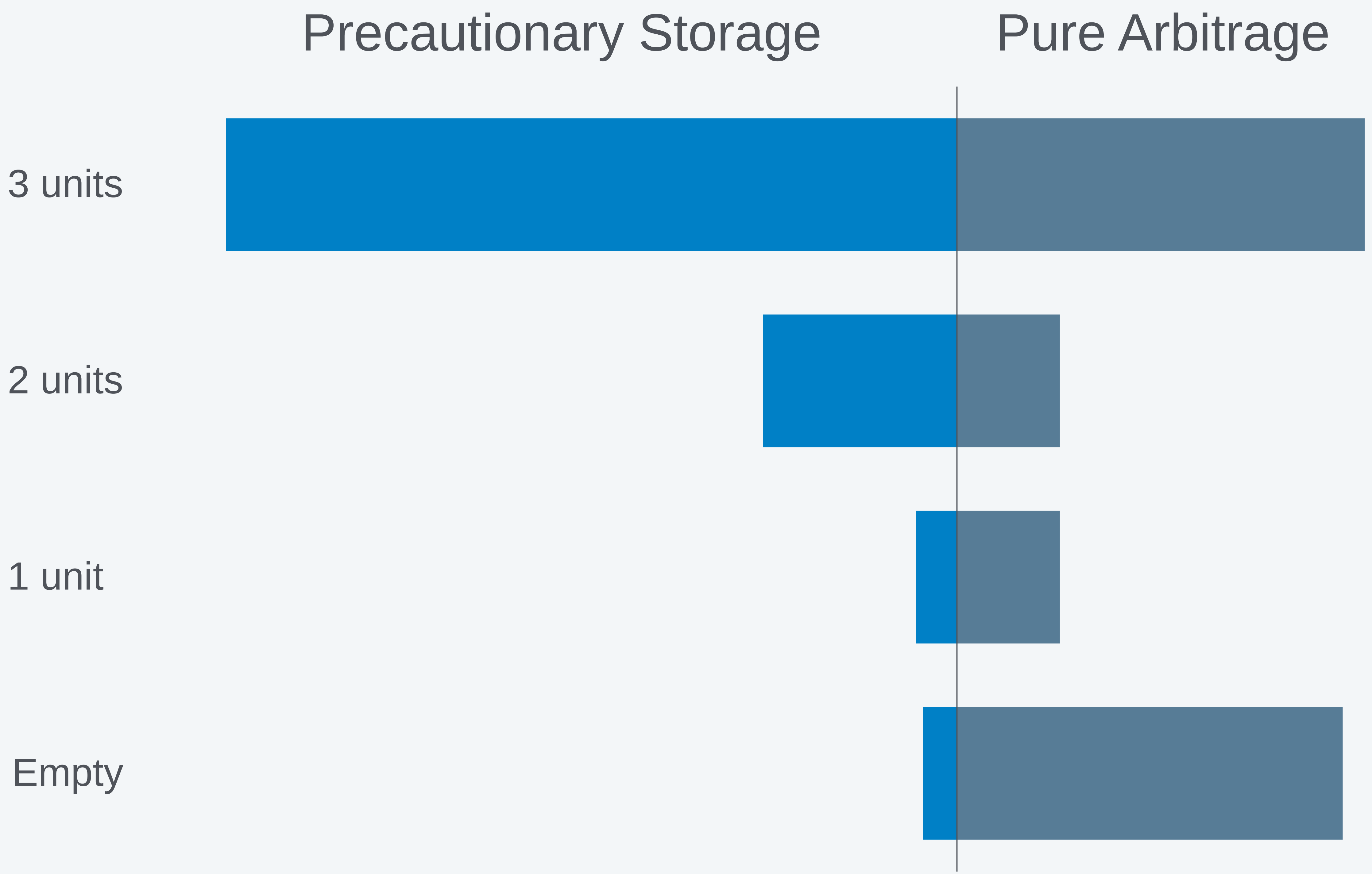


Load-duration Curve

“Precautionary storage” strategy



Distribution of storage states



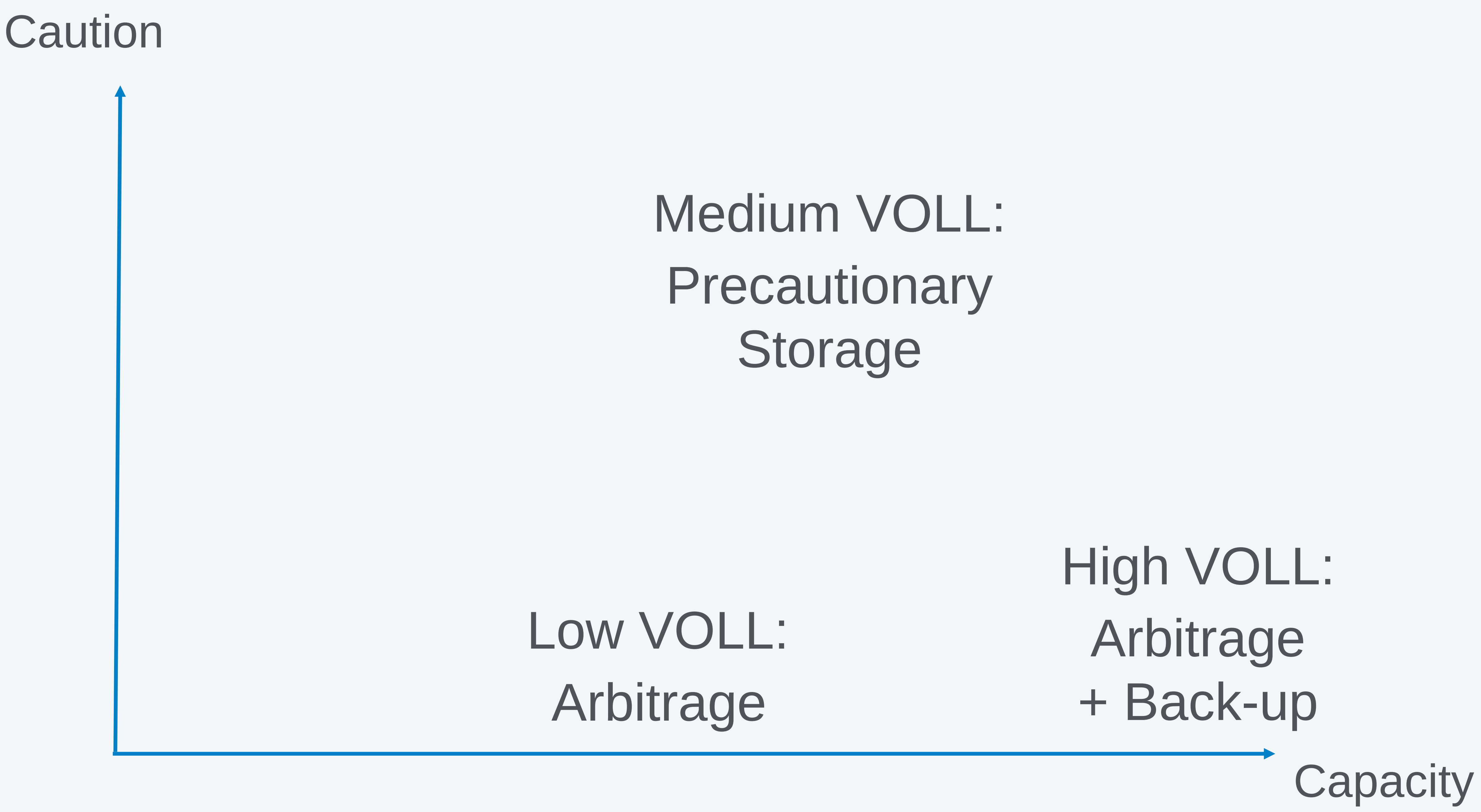
Savings from storage
(excluding cost of storage units)

Pure Arbitrage saves 1% of total cost

Precautionary Storage saves 2.4%

The role of VOLL

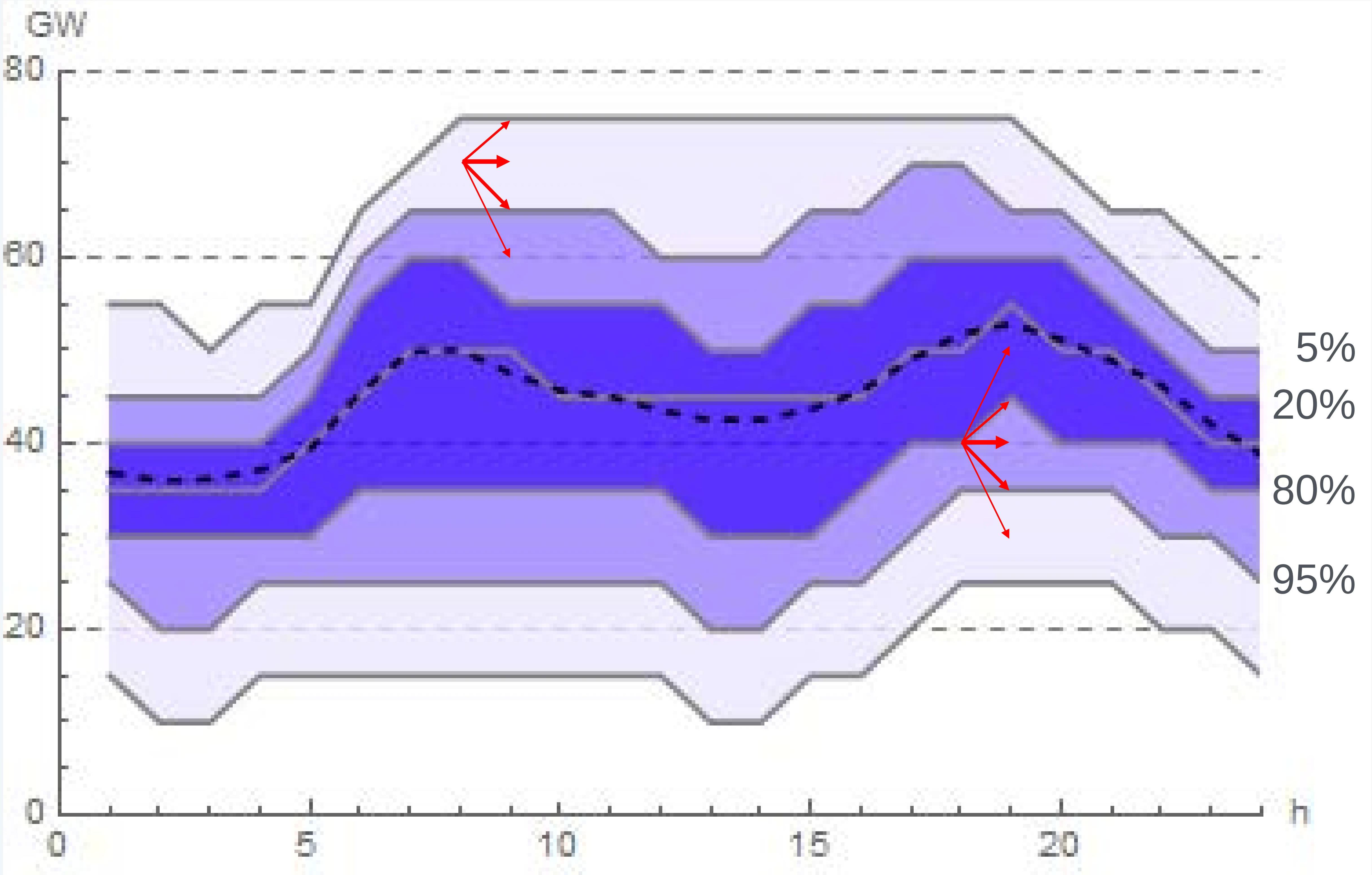
Optimal risk of outage linked to Value of Lost Load



A calibrated model

Load as a diurnal Markov Chain

Distribution and transition probabilities



Load as a diurnal Markov Chain

Mathematical representation

Transition matrices P_h with $h = 1, \ldots, 24$

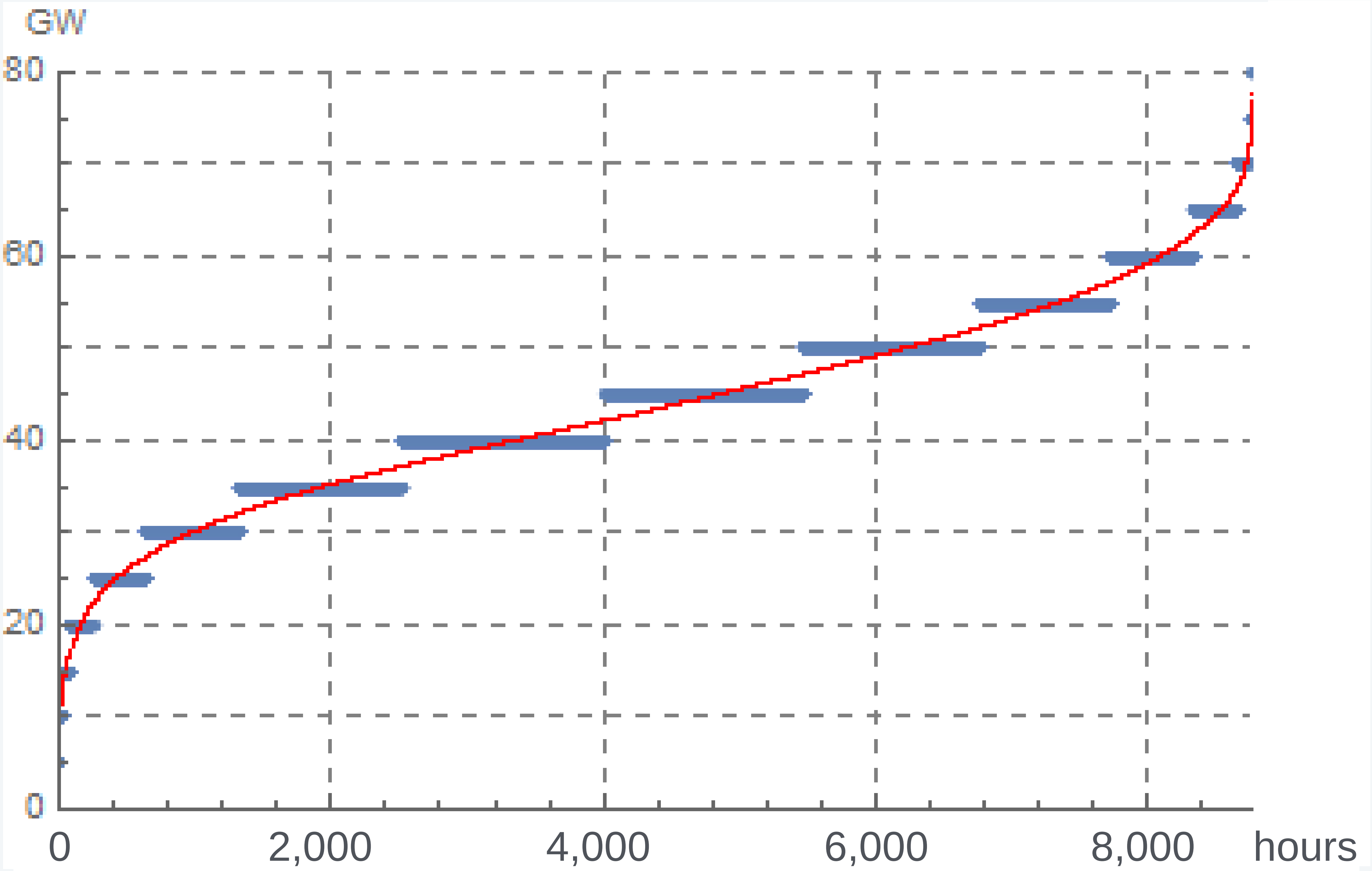
P_1 gives probability of each state at $h = 2$, given s_1

Steady-state distribution at $h = 1$, p_1^*, given by

$$p_1^* = p_1^* \cdot P_1 \cdot \ldots \cdot P_{24}$$

Load as a Markov Chain

Load-duration curve for German data, 2011-15

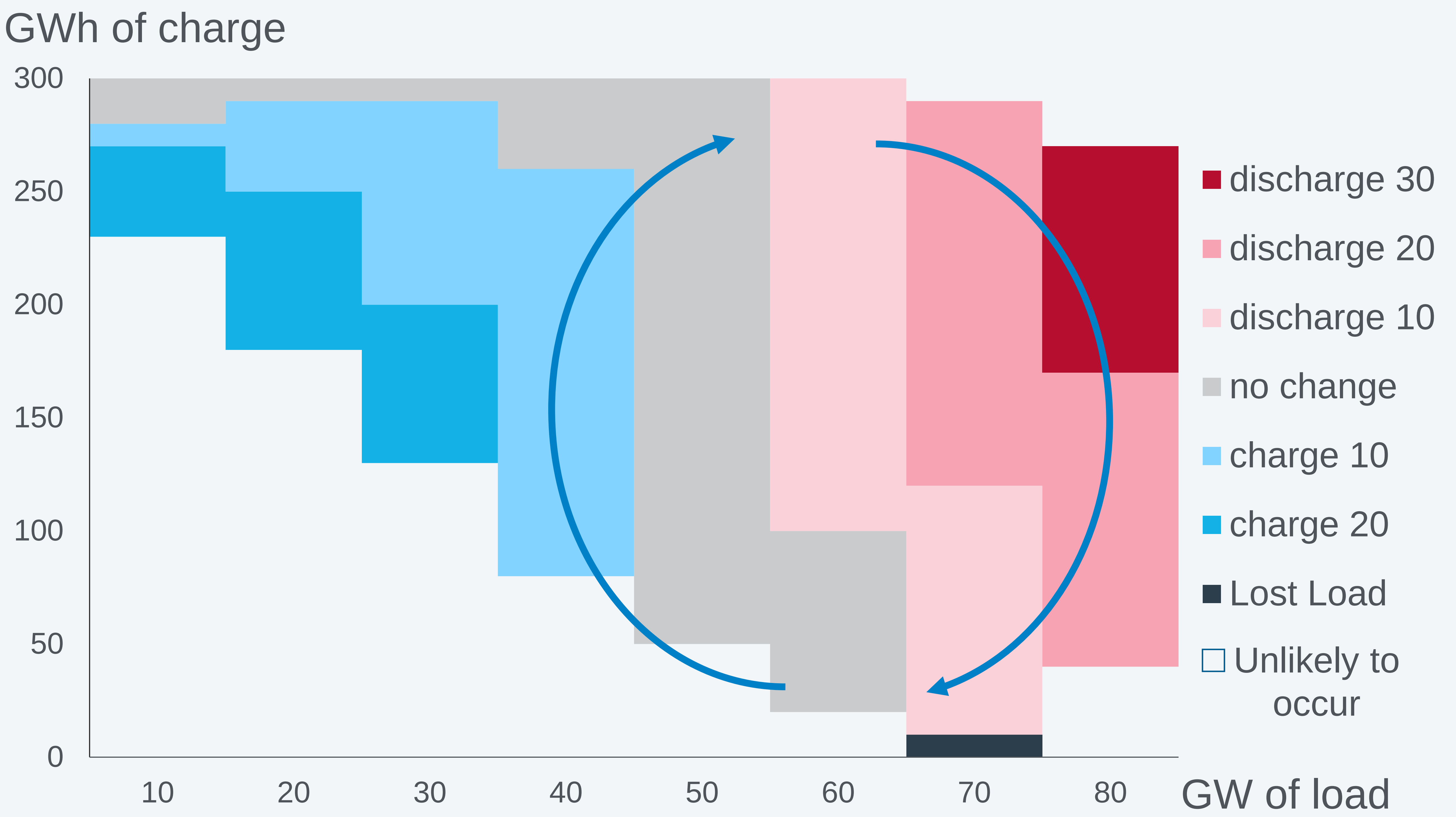


Cost data

Technology		Nuclear	Lignite	Coal	Gas CCGT	OCGT	Lost Load
Variable Cost (Fuel + variable O&M)	€/MWh	14	38	42	54	74	20,700
Fixed cost (Capital cost and fixed O&M)	€/KW-year	387	189	163	103	55	0
Breakeven load factor [%]		92.9	78.0	57.2	28.0	0.03 = 3h/a	
Source: derived from Schröder et al., 2013.							

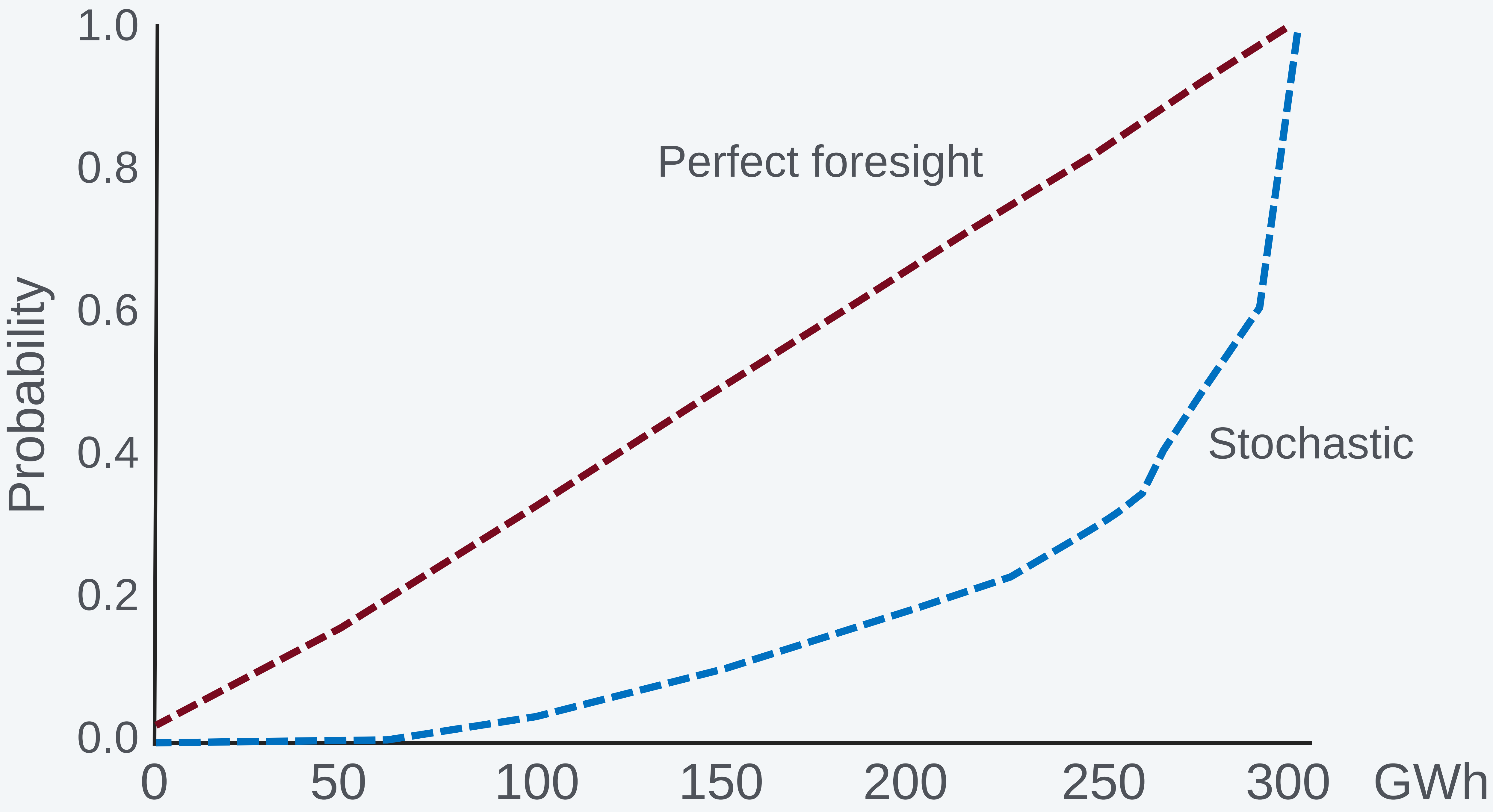
Charging strategy

10 GW version of the model



Expected state of charge

10 GW version of the model



Cost comparisons

Storage capacity	Comment	Variable	Fixed	Total	Storage Value
GWh		€/MWh	Mio €	Mio €	€/kWh/y
Perfect foresight					
0	Continuous residual load 2011-2015	26.41	15,829	25,923	
0	Optimising against specific 5-year simulations of the Markov residual load.	27.59	15,316	25,823	

Cost comparisons

Storage capacity	Comment	Variable	Fixed	Total	Storage Value
GWh		€/MWh	Mio €	Mio €	€/kWh/y
Perfect foresight					
0	Continuous residual load 2011-2015	26.41	15,829	25,923	
300		21.43	16,309	24,500	4.74
0	Optimising against specific 5-year simulations of the Markov residual load.	27.59	15,316	25,823	
300		20.67	16,364	24,287	5.12

Cost comparisons

Storage capacity	Comment		Variable	Fixed	Total	Storage Value
GWh			€/MWh	Mio €	Mio €	€/kWh/y
Perfect foresight						
0	Continuous residual load 2011-2015		26.41	15,829	25,923	
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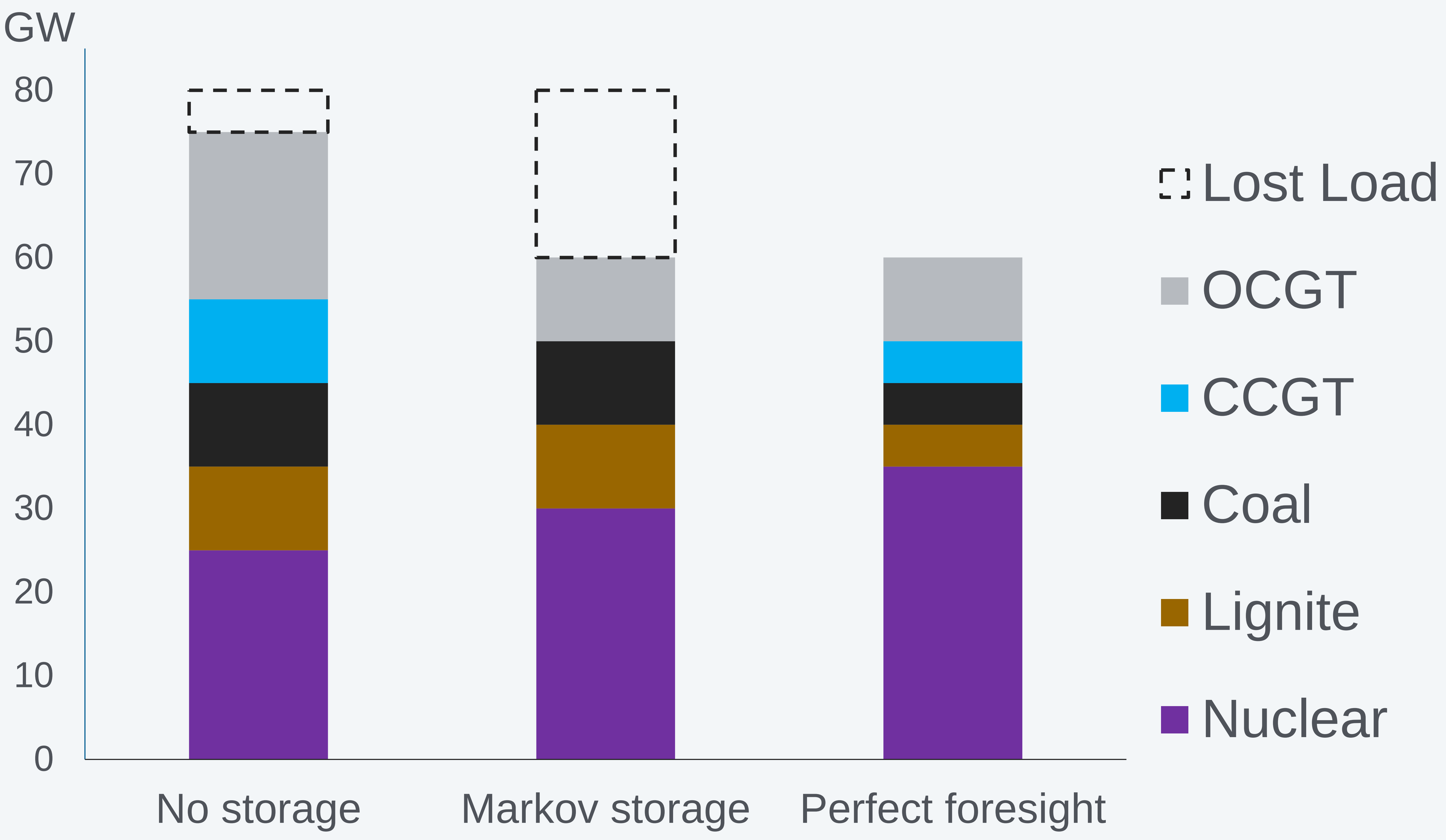
300			20.67	16,364	24,287	5.12
Stochastic residual load						
0	Optimized capacities		27.69	15,316	25,899	
300	Opt. storage management	not adjusted capacities	26.30	15,316	25,368	
300		adjusted capacities	23.55	15,678	24,679	4.07

Capacity choices



Extensions

Using daily load profiles (chosen by clustering)

Adding forecasts (imperfect) of which profile comes next day

Finer-grained states of demand and storage