Wirtschaftlich-technische Systemanalyse für Batteriespeicher in stationären Anwendungen

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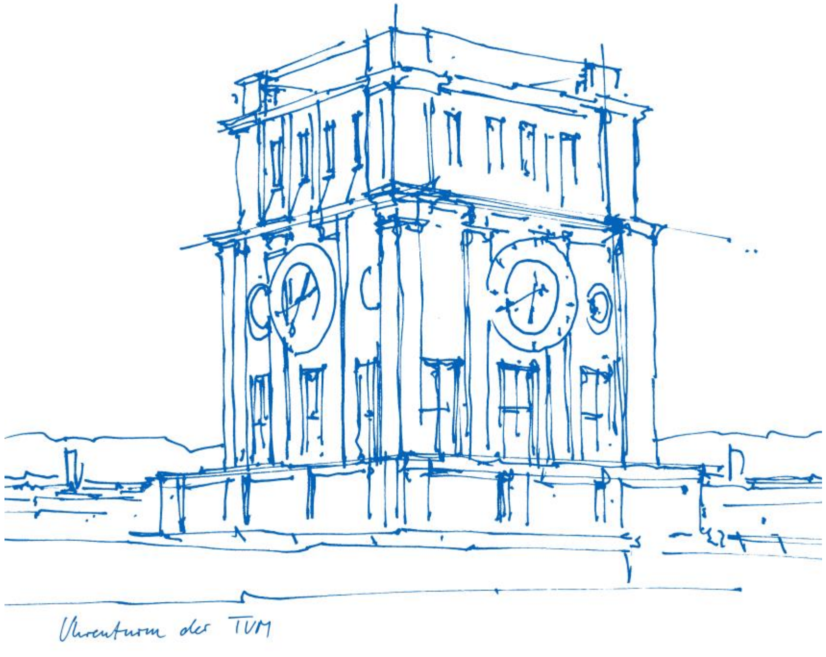


Gliederung

Übersicht stationäre Anwendungsfälle und Speichersysteme

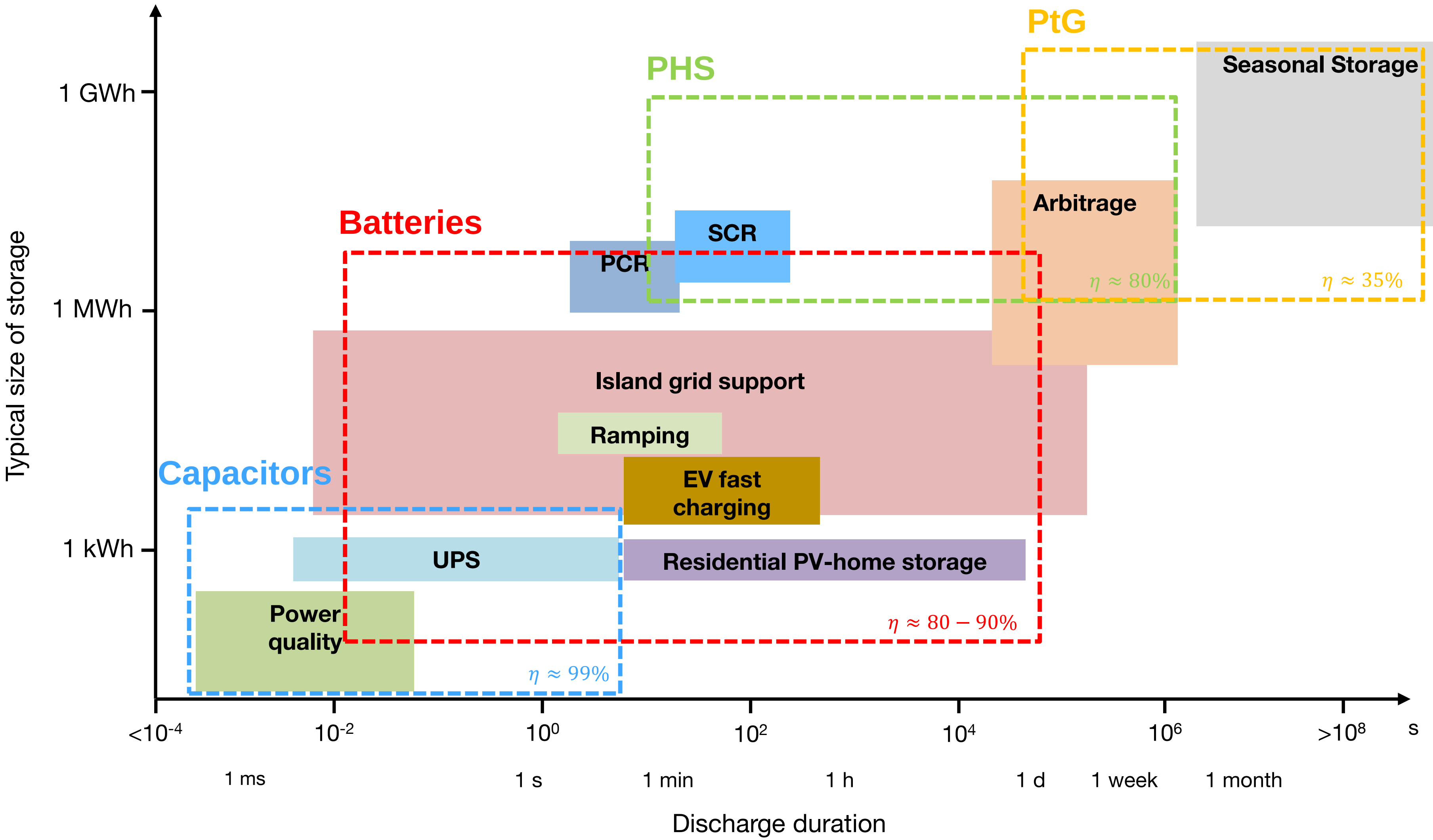
Wirtschaftlich-technische Modellierung von Batteriespeichern

- **Modellansatz**
- **Kostenfaktoren für Speichersysteme**
- **Alterungsmechanismen (Li-Ionen)**
- **Anwendungsbeispiele**

Ausblick zur Systemhybridisierung

Application fields for stationary energy storage

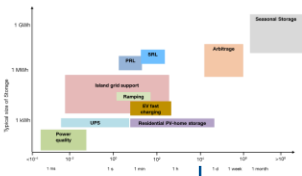
Classification of reaction speed and typical energy demand



SimSES: Storage modelling tool

Matlab tool for storage behavior modelling and assesment of economic value

Application specific time series data



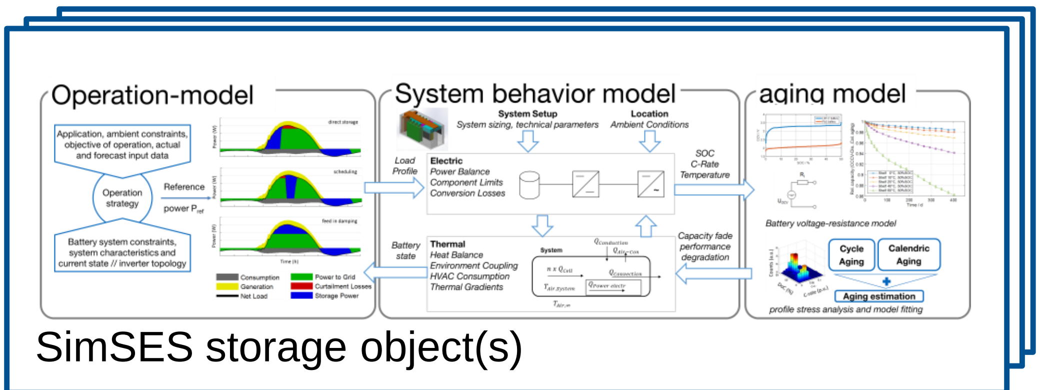
Economic data

EES cost
Energy market data

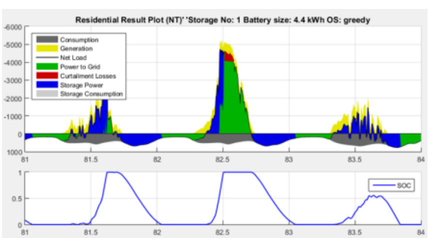
Storage system information

EES type (LFP, PbS, RFB, PtG)
Topology (XX s YY p)
Inverter coupling (AC / DC)

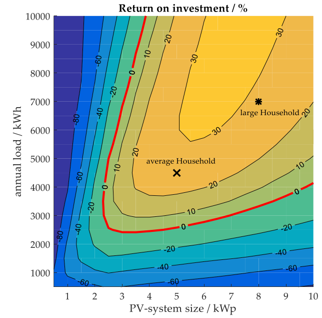
Performance and aging measurements



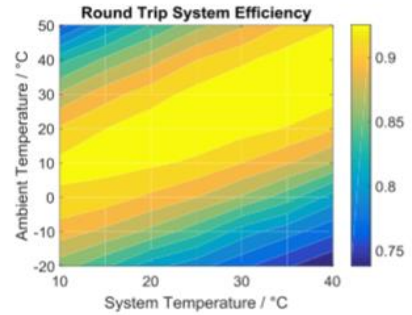
Simulation of storage operation



Economic assessment

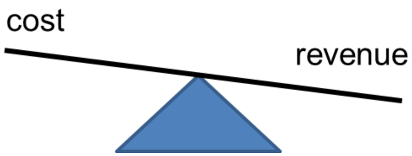


Evaluation and result analysis



Economic assessment of stationary storage

Return on invest and levelized cost of energy



$$ROI = \frac{"Profit"}{Invest} = \frac{"Revenue - Cost"}{Invest}$$

Revenue

Application-specific:
PRL, SRL: weekly auction
Home -Storage: avoided retail electricity tarif

Peak-Shaving: reduced peak power price
Island-grid: avoided fuel cost for generator
…

$$Cost - for\ a\ battery\ storage\ system$$

$$C_{Batt} = C_{CAPEX} + C_{OPEX} + C_{replace}$$

$$C_{CAPEX} = k_{Batt} * E_{batt} + k_{PE} * p_{max} + k_{fix}$$

$$C_{replace} \rightarrow \frac{k_{Batt} * cap}{LD_{Batt}} + \frac{k_{LE} * p_{max}}{LD_{LE}}$$

$$C_{OPEX} = f(\eta_{Batt}, \dots)$$

$$LCOE = \frac{K_{cost,Batt}}{\sum E_{Storage}^{out}} = \frac{K_{CAPEX} + K_{OPEX} + K_{replace}}{\sum E_{Storage}^{in} * \eta_{sys}}$$

Battery storage cost

$$k_{Batt} \approx 300 - 700\ €/kWh$$
$$k_{PE} \approx 100 - 200\ €/kW$$

$C_{replace}$- lifetime of storage

$$LD_{Batt} \approx 2 \dots 20\ a$$

$LD_{Batt} \rightarrow f(Application)$

$LD_{Batt} \rightarrow f(OS)$

OPEX: operational cost (power, maintenance, HR)

$$\eta_{sys} \approx 60 \dots 90\%$$

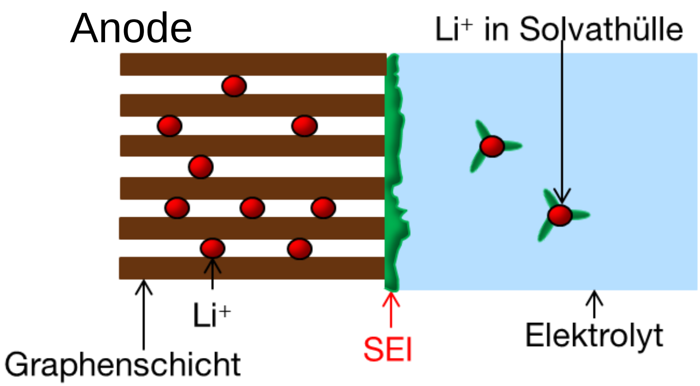
$\eta_{sys} \rightarrow \eta_{batt} * \eta_{PE} * \eta_{per}$

$\eta_{batt} \rightarrow f(technology)$

$\eta_{Batt} \rightarrow f(OS)$

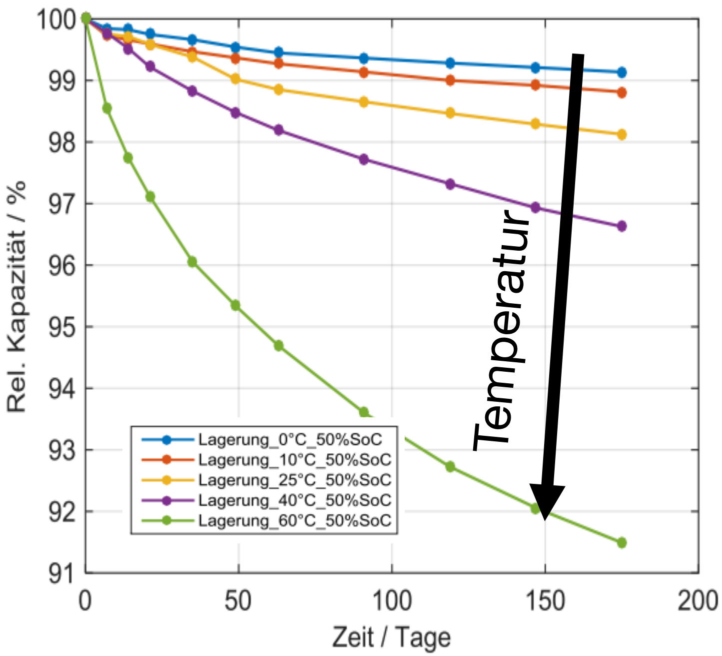
Alterung im Batteriespeicher: Li-Ionen

Li-Ionen: kalendarische Alterung



- **Elektrolytzersetzung:**
  - SEI Wachstum
  - Deg. bei hohem SOC, hoher Temperatur
- **Kathodenauflösung**:
  - Spezifisch je nach Kathode
  - Deg. z.T. bei hohem SOC

$$a_{kal} \approx f(SOC, T, \dots)$$



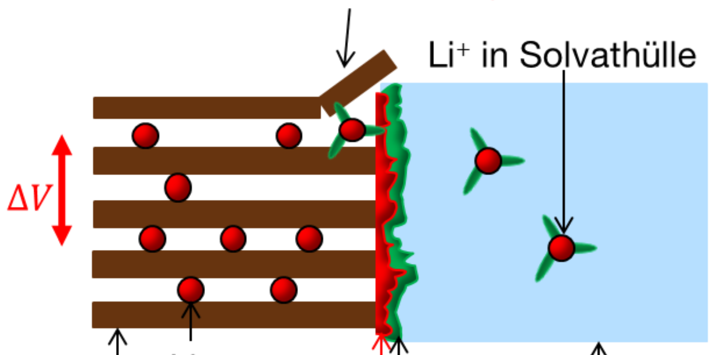
Arrhenius-Charakteristik

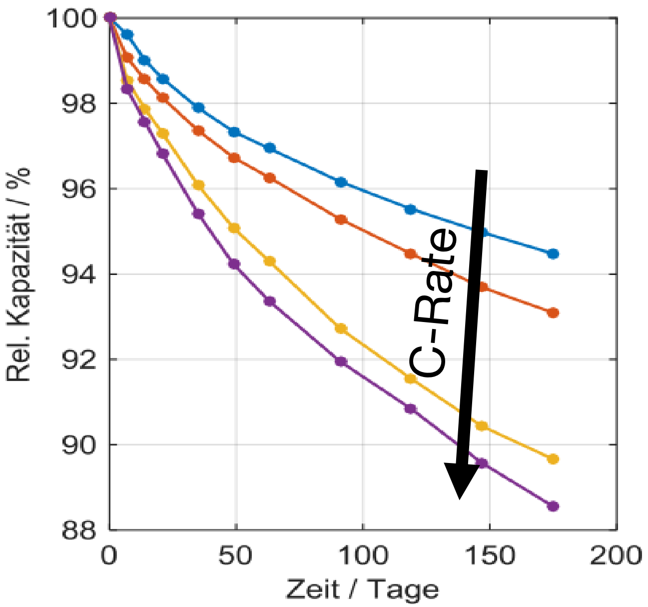
$$k = k_0 \cdot e^{-\frac{E_a}{R \cdot T}}$$

k	Reaktionsgeschwindigkeit
k_0	Präexponentieller Faktor
E_A	Aktivierungsenergie
R	Univ. Gaskonstante
T	Temperatur in Kelvin

Alterung im Batteriespeicher: Li-Ionen

Li-Ionen: zyklische Alterung





- **Volumenarbeit**
  - Deg. bei hohen Strömen, hohem DoD
- **Li-Plating**
  - Deg. bei hohen Strömen, tiefen Temperaturen
- **Phasenübergänge & Interkalation**
  - Deg. z.T. auch bei mittlerem SOC prominent

$$a_{zyk} \approx f(C_{rate}, T, \overline{SOC}, DOD, \ldots)$$

Häufig: Superpositionsprinzip Alterung

$$a_{ges} \approx a_{zyk} + a_{kal}$$

$\Longrightarrow$ Optimale Betriebstemperatur Li-Ion ≈ 25 °C

Alterung im Batteriespeicher

Stationäre Anwendungen und zu erwartende Alterungsform

$$a_{ges} \approx a_{zyk} + a_{kal}$$

	C-rate Stromrate bei typ. P/E Speicher	Zyklenanzahl	DoD	typischer SoC	Vorherrschende Alterungsform für LIB
Arbitrage	Niedrig	Mittel	Tief	Hoch / niedrig	**Kalendarisch + zyklisch**
Peak-Shaving	Mittel	Niedrig	Tief	Hoch	**Kalendarisch + zyklisch**
Bereitstellung von PRL (Regelleistung)	Hoch	Hoch (Mikrozyklen)	Flach	Mittel	**Kalendarisch + zyklisch**
Netzstützung	Niedrig	Niedrig	Tief	Mittel	**Kalendarisch**
PV-Heimspeicher	Niedrig	Mittel	Tief	Mittel	**Kalendarisch + zyklisch**
USV	Hoch	Sehr niedrig	Flach	Hoch	**Kalendarisch**

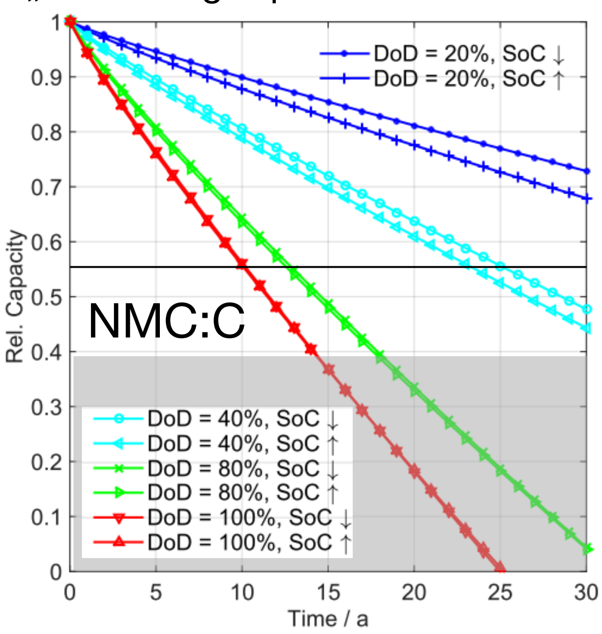
→ Farbprofil zeigt qualitativ Alterungseinfluss bei Verwendung typischer Li-Ionen Batterien

Alterung im Batteriespeicher

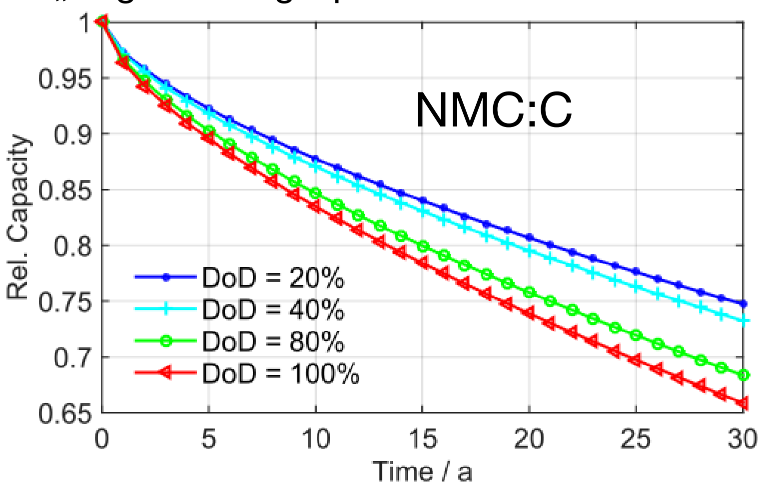
Alterung in beispielhaften stationären Anwendungsszenarien

- Modellierungsexperiment für automotive NMC:C Zellchemie
- Alterungseinfluss in unterschiedlichen Anwendungsszenarien

„Heimenergiespeicher“



„Regelleistungsspeicher“



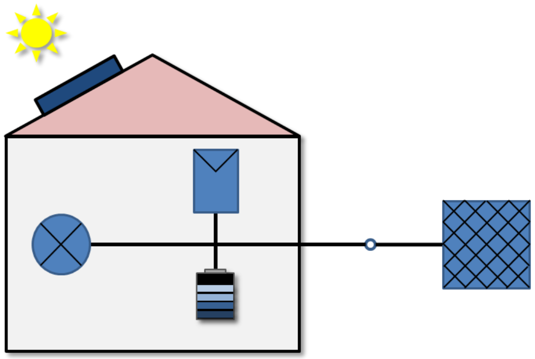
Alterungsverlauf abhängig von Zellchemie und Anwendungsszenario!

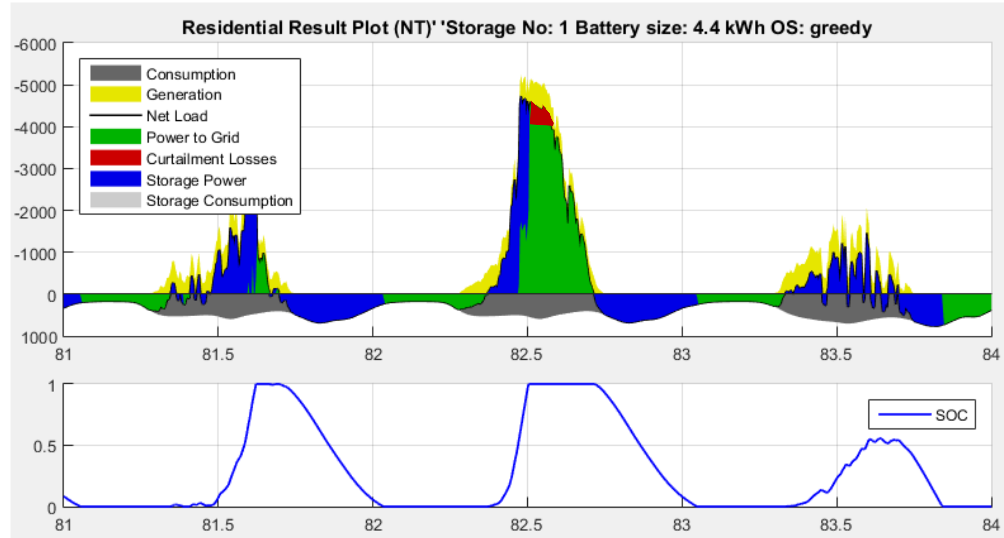
Studie Sebastian Fischhaber, Annika Regett, Simon Schuster, Holger Hesse: „Second-Life Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen“ (2016)

Residential PV & home storage

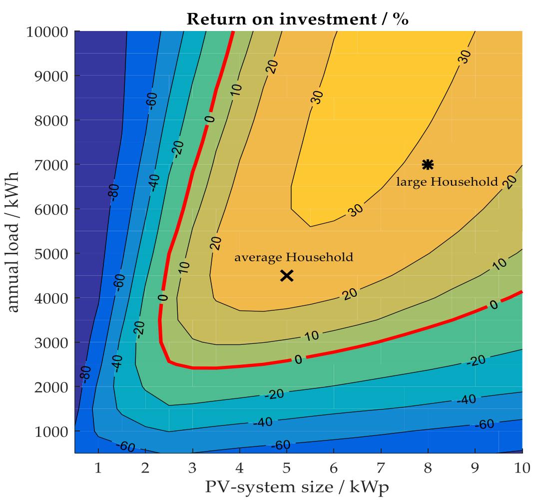
Residential PV-home storage

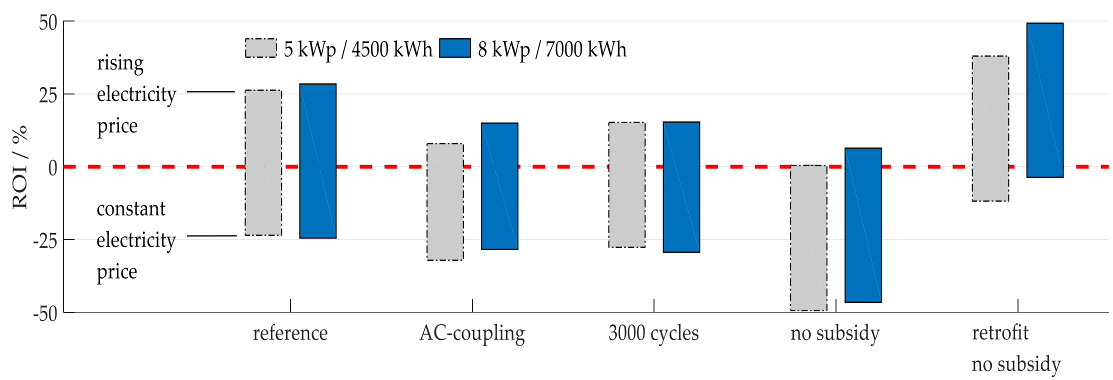
Cost & Revenue analysis – „Tesla Powerwall®“





Rising electricity price (4,55 p.a.)





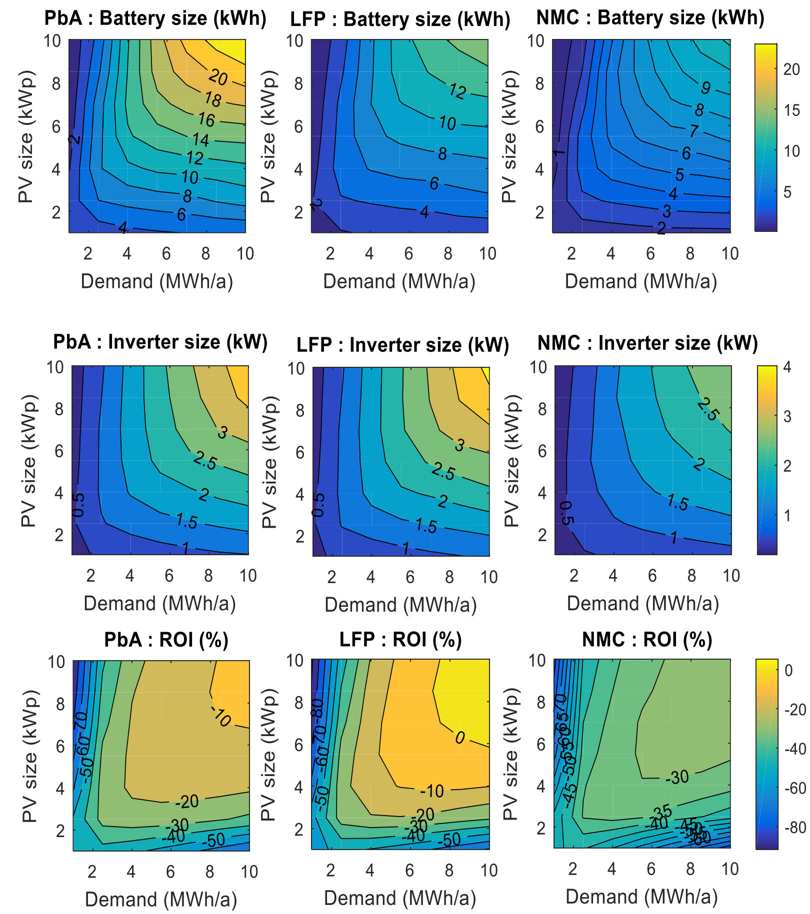
[“Economics of residential photovoltaic battery systems in Germany: The case of Tesla’s Powerwall”]

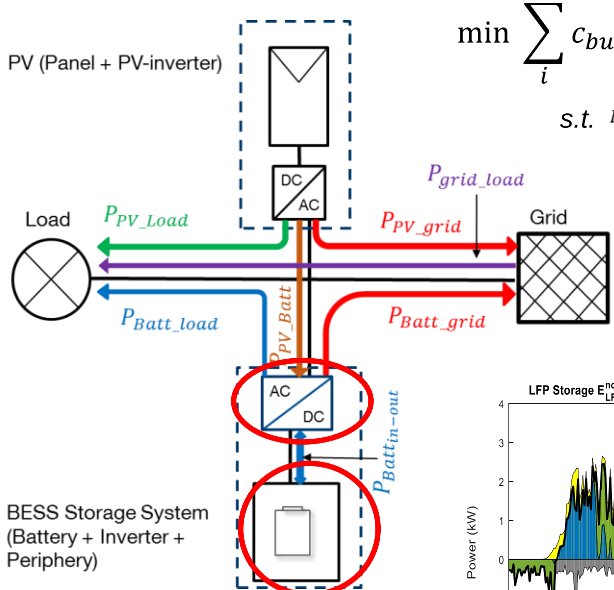
C.N. Truong, M. Naumann, R.C. Karl, M. Müller, A. Jossen, H.C. Hesse, *batteries 2016,2 (2)*

Residential PV & home storage

Optimization of component dimensioning & power flow

- Linear programming approach to battery storage size and inverter size optimization
- Calendar and cyclic aging model
- Battery type comparison: PbA, NMC, LFP
- Slightly positive ROI for LFP in some scenarios



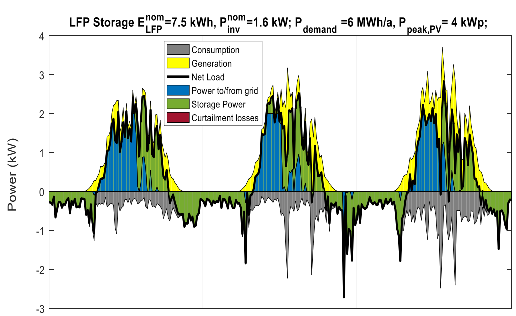


$$\min \sum_i c_{buyE,i} - r_{sellE,i} - \deg_{storage}$$

s.t. $P_{pv_i} = P_{pv-load_i} + P_{pv-batt_i} + P_{pv-grid_i} + P_{curtail_i}$

$$P_{pv-grid_i} + P_{curtail_i} \leq P_{feed-in}^{max}$$

$(\ldots)$

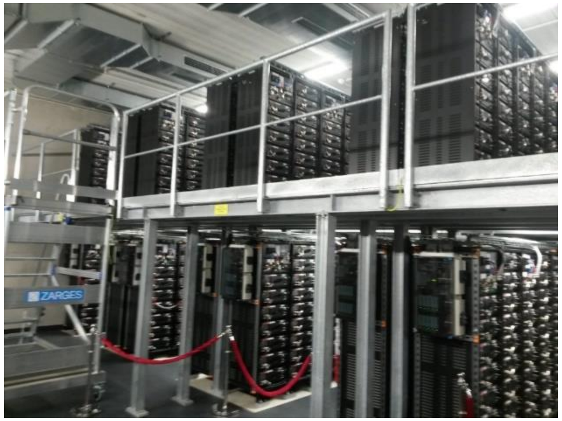


“Tailoring battery storage for PV-home applications: Finding the best technology and component sizing using linear optimization“
H.C. Hesse, R. Martins, P. Musilek, M. Naumann, N. Truong, A. Jossen, submitted

Control reserve

Frequency regulation (PRL, SRL)

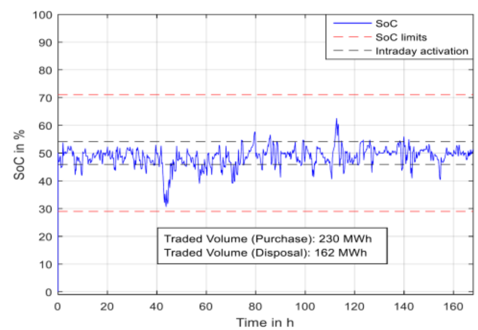
PCR: Storage energy management strategy and aging determination

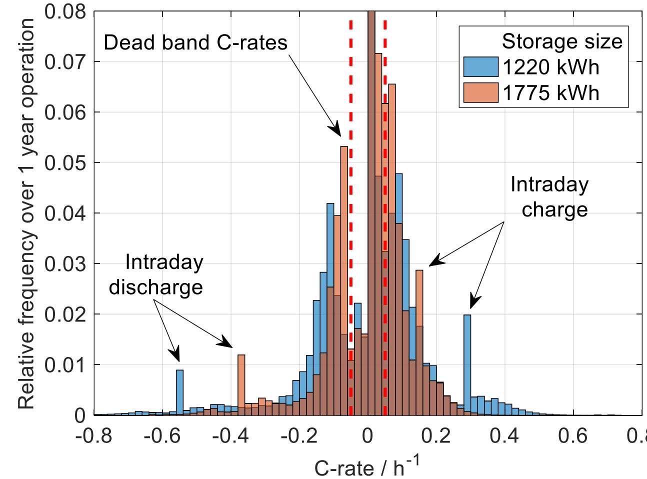


WEMAG 5MWh PCR battery storage

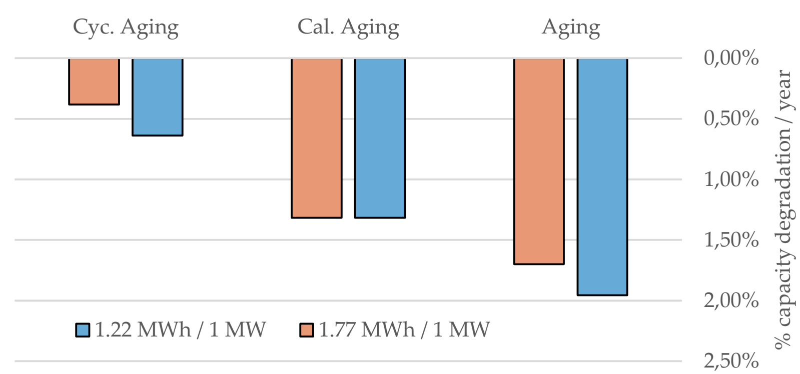
Battery PCR provision framework

- 15 / 30 min criterion
- Dead-band $50 \pm 0.01\ Hz$
- Intraday EEX trading
- Over-supply 100…120%
- Ramp control speed (0…30s)





- Development of battery storage operation strategy for PCR compliant to 2016 regulations
- Storage aging analysis using historical data
- Comparison of different sizing approaches
- Investigations on combined use cases (e.g. home storage + PCR)



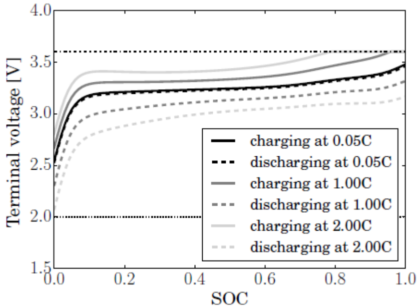
„Fundamentals of using Battery Energy Storage Systems for providing Primary Control Reserve“
M. Müller, A. Zeh, M. Naumann, H.C. Hesse, A. Jossen, R. Witzmann, *batteries, 2(3),29*

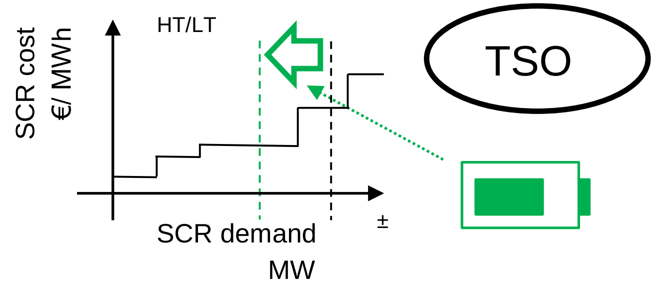
Storage application fields

Frequency regulation (PCR, SCR)

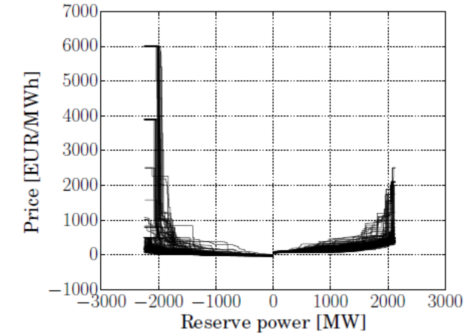
Ancillary services – frequency control

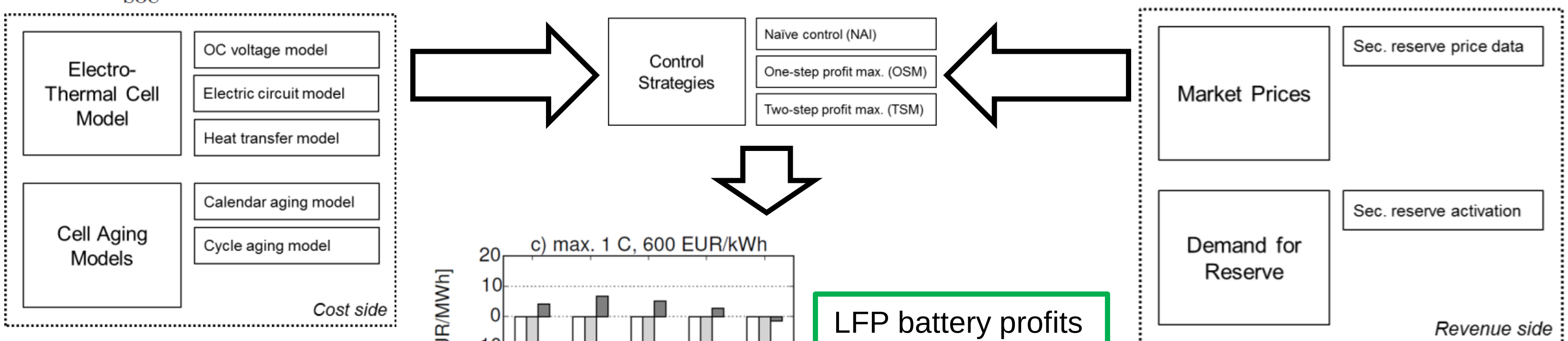
Battery ECM model

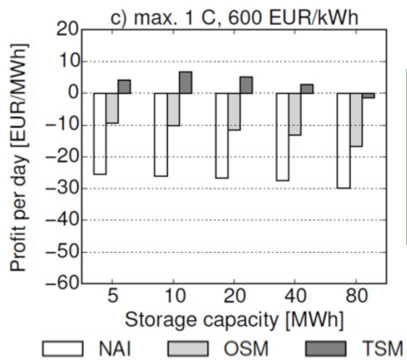




Historical SCR energy delivery price

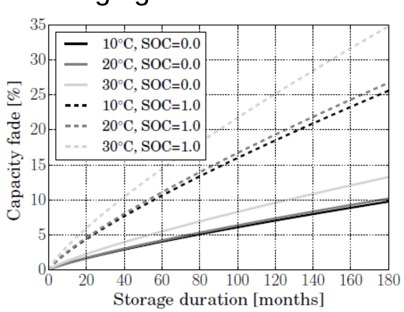




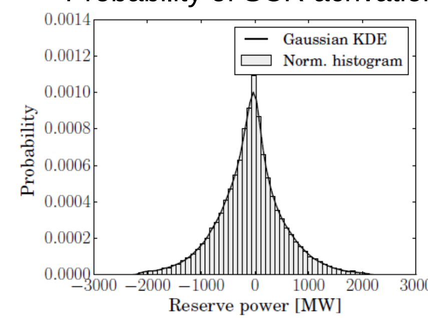


LFP battery profits in SCR application at battery prices below 600 €/kWh

LFP Aging model



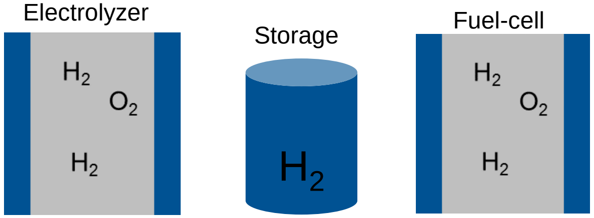
Probability of SCR acrivation



„Model-based Dispatch Strategies for Lithium-Ion Battery Energy Storage Applied to Secondary Reserve Provision"
C. Goebel, H.C. Hesse, M. Schimpe, A. Jossen, H.-A. Jacobsen, IEEE Transactions on power systems (2016) in press

Power-to-Gas und Hybridisierung

Power-to-Gas + Battery Hybridization



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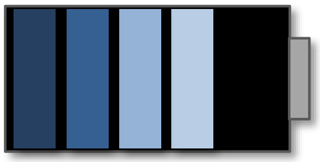
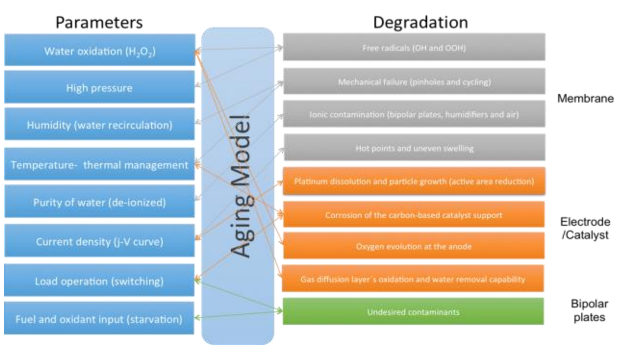
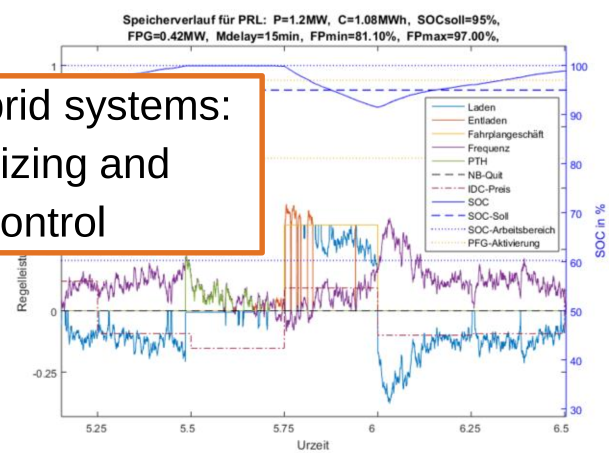


Power-to-Gas:				Batteries:
- Low conversion efficiency	$\eta_{PtG} \approx 35\%$	η	$\eta_{PtG} \approx 90\%$	- High conversion efficiency
- Very low energy related cost	$++$	k_E	$--$	- High energy related cost
- High power related cost	$-$	k_p	$++$	- High peak-power capability
- Aging: sensitive to on/off cycles model development in progress		$a_{tot} = f(\dots)$		- Aging: sensitive to charge throughput, DOD

Electrolyzer & Fuel Cell Aging Model



Optimize hybrid systems: component sizing and operational control



Example-plot: PCR with hybrid system battery + PtH