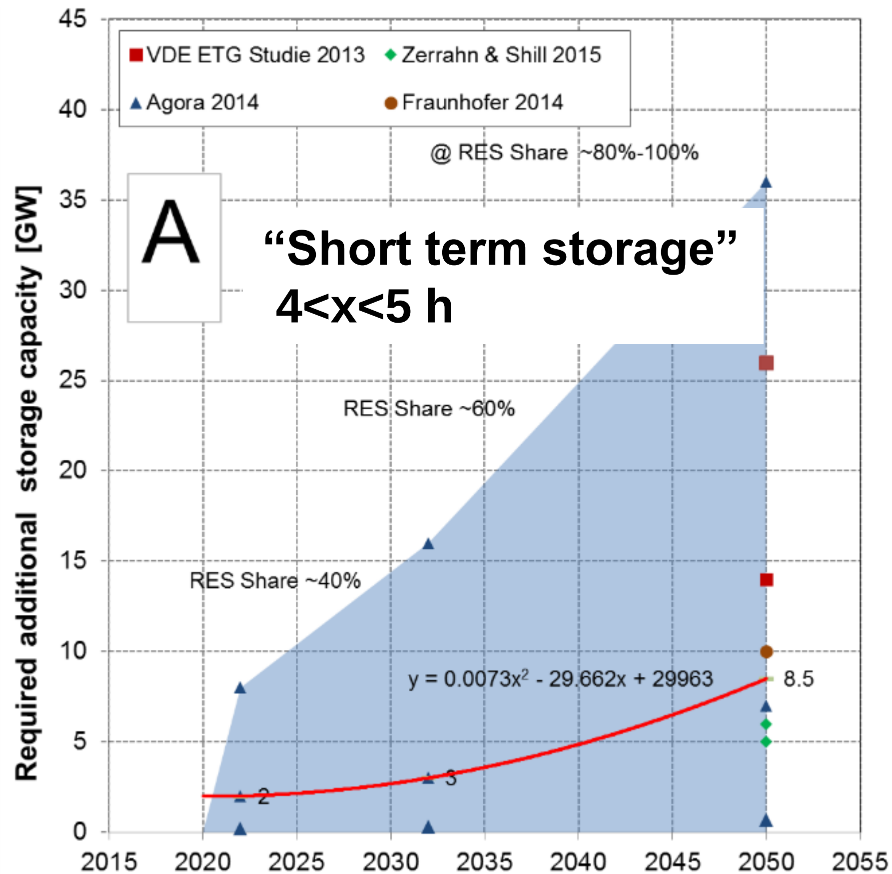
How to benchmark hybrid- and electro-chemical energy storage systems

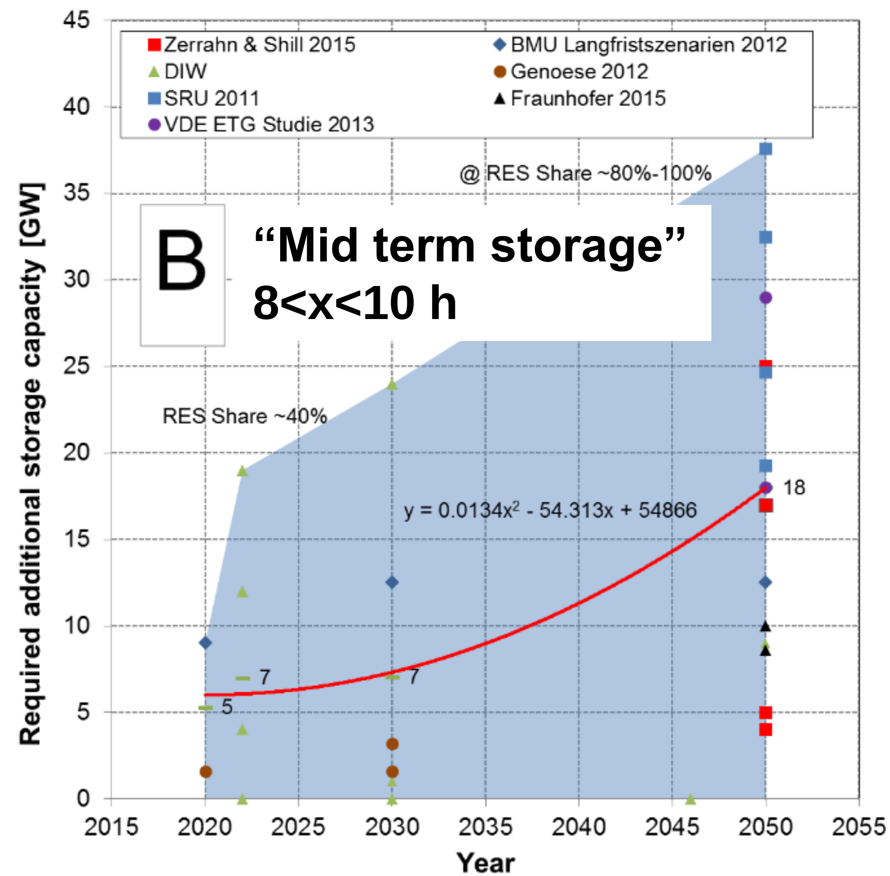
Manuel Baumann[1], Marcel Weil[1,2], Jens Peters[2]
[1]Institute for Technology Assessment and System Anayses - Karlsruhe Institute of Technology
[2]Helmholtz Institute Ulm - Karlsruhe Institute of Technology

Joint "EERA – ON-SITE Project" Workshop on Hybrid Energy and Energy Storage Systems 21 - 22 September 2017 Ericsson – Via Anagnina 203, 00118 Morena, Rome, Italy

Introduction

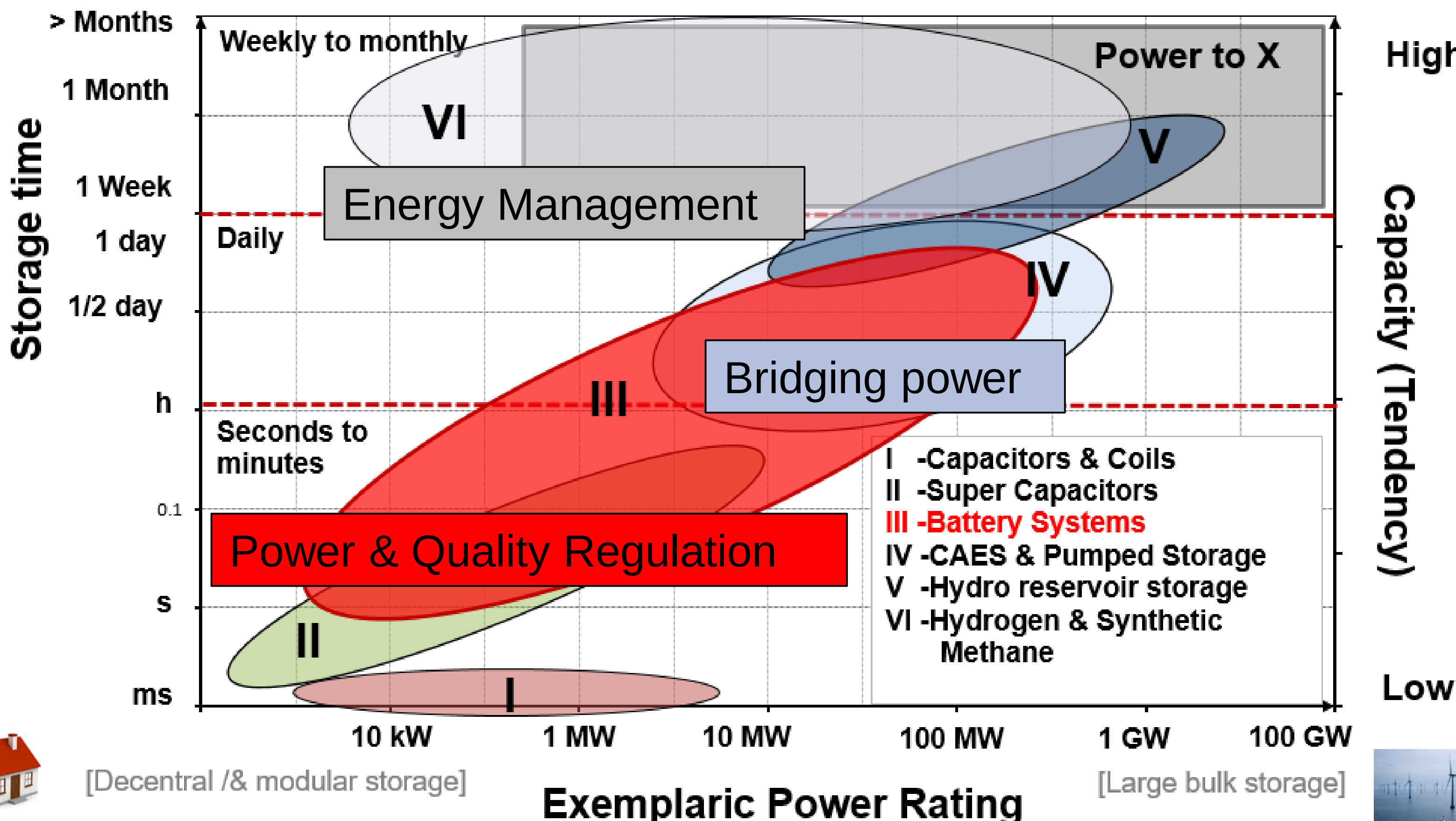
- German Energy transition → > 80 % share of RES in 2050
- Increasing demand for energy storage technologies





Introduction

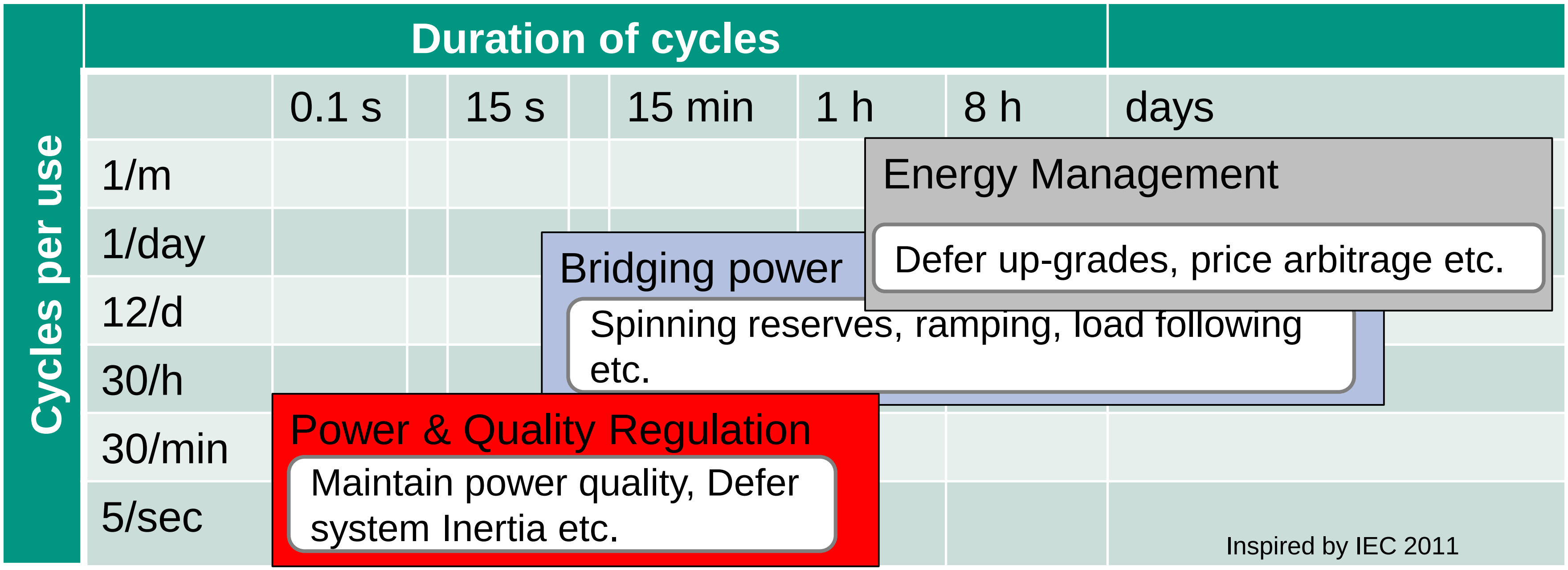
- Several Energy Storage Technologies are available
- No technology is able to cover all grid applications in the near term



Inspired by Sauer et. al 2010

Introduction

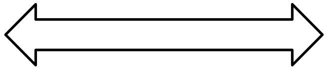
- Multiple application fields → each with specific requirements



P&Q - Regulation

- **Response time**
- Cycles / cost
- …

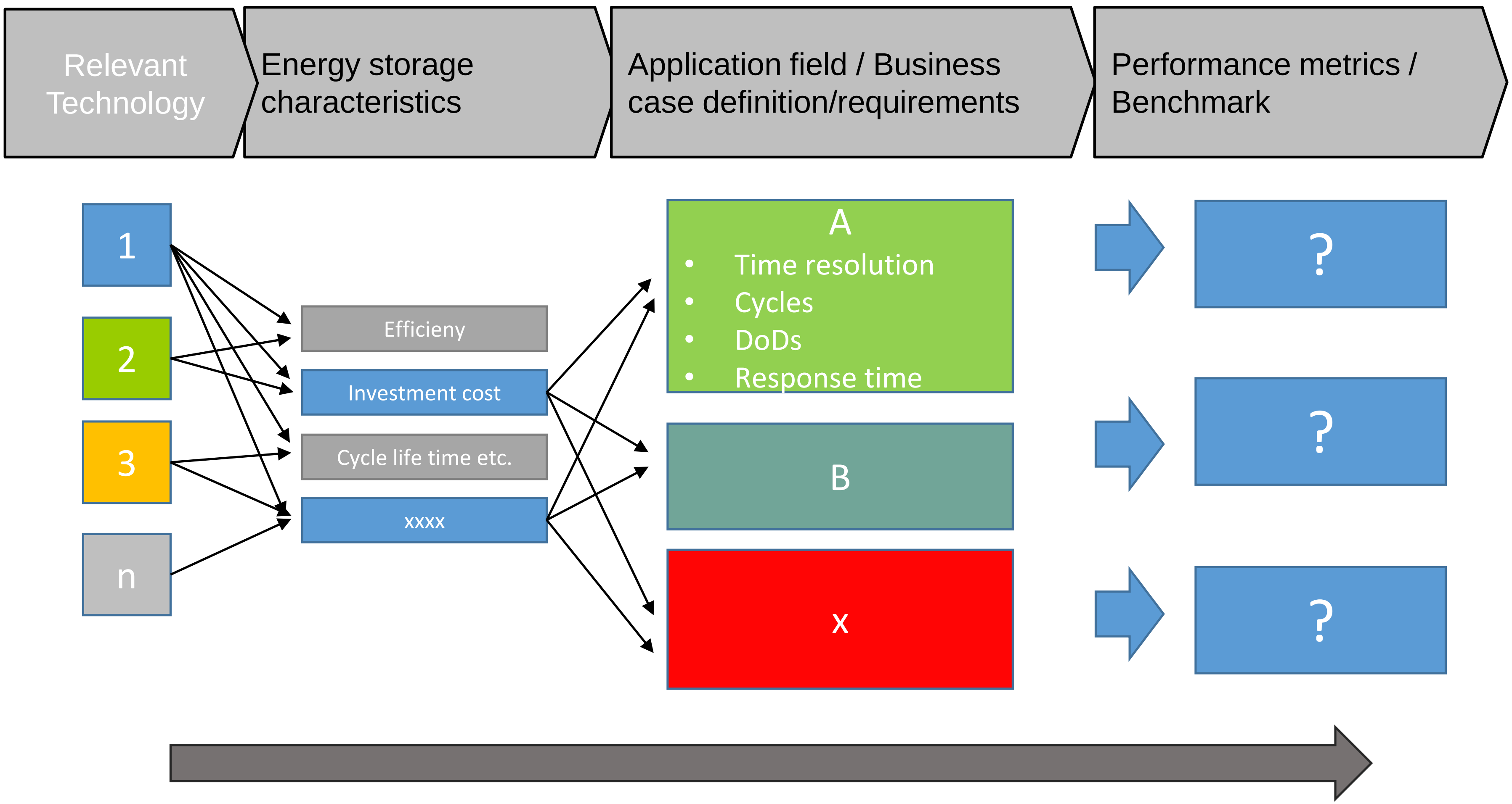
Criteria are the same but priorities are different



Energy management

- **Cycles / costs**
- Response time
- …

Benchmarking Energy Storage: General approach



Which technology is suitable to which application?
Which one performs best?

Benchmarking Energy Storage: Overview

- **Benchmarking dimensions, methods and metrics**
  - **Techno-Economic:**
    - Levelized cost of Electricity €/MWh
    - Total installed capital cost €/kW
    - Levelized Cost of Capacity €/kW-Yr
    - Life Cycle Cost €/MWh

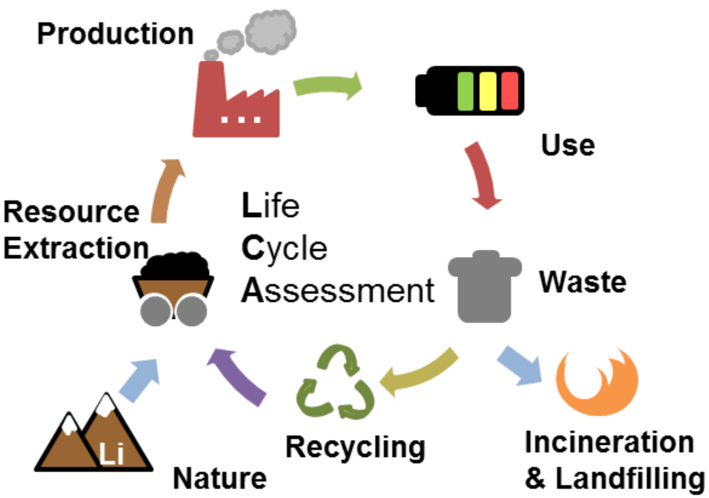
  - **Environmental:**
    - Life Cycle Assessment
      - Carbon footprint kgCO_2 eq./kWh
      - Others

  - **Social:**
    - Acceptance of technologies
    - Social Life Cycle Assessment

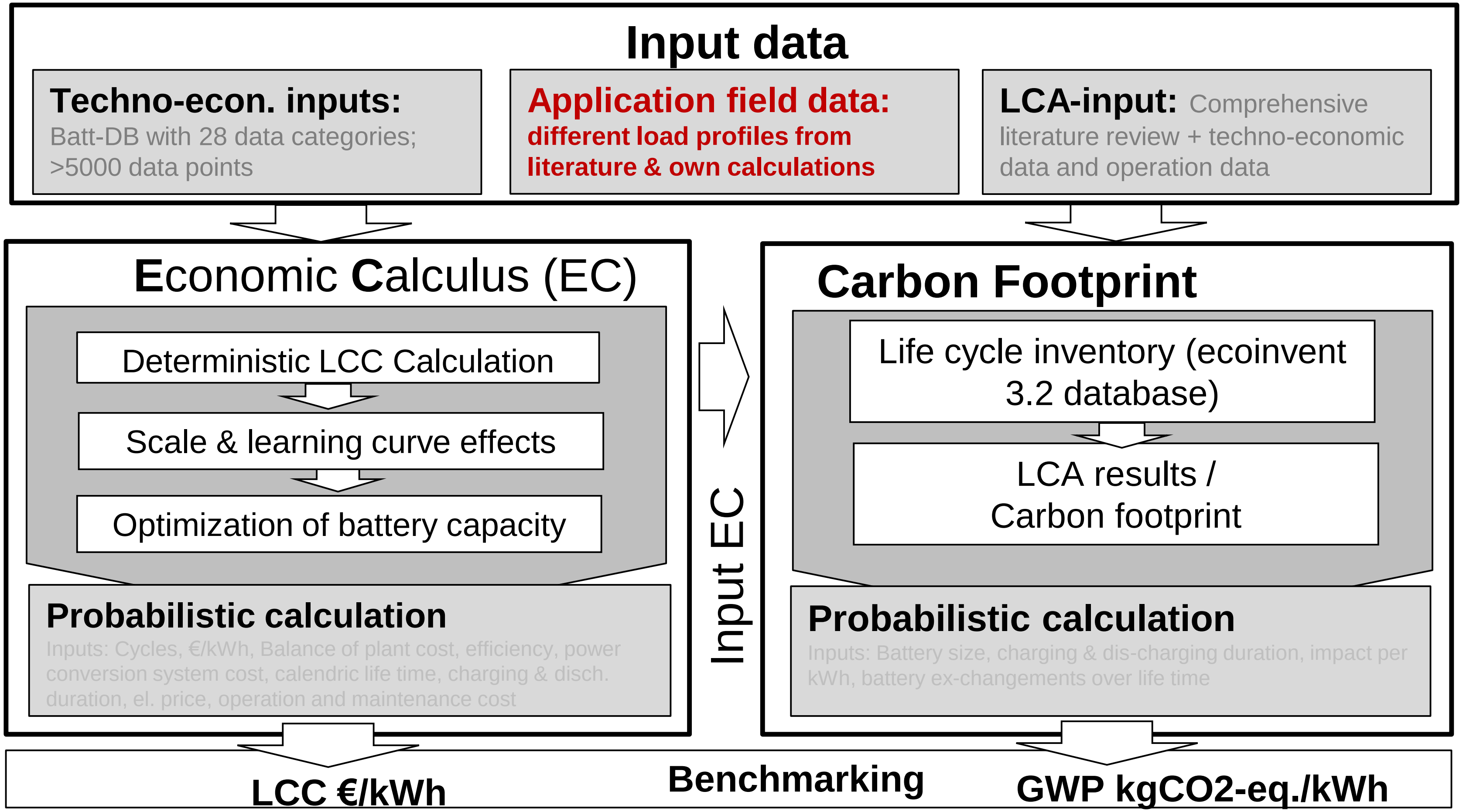
Benchmarking energy storage: Example for two approaches

- Life cycle costing (LCC) systematic comparison over the whole economic life time of a product.
  - Initial investment, capital, replacement, operation, energy and disposal costs etc.
  - IEC 60300-3-3 or VDI 2884
  - E.g. Annuity method, NPV etc.

- Carbon footprint → greenhouse gas (GHG) emissions
  - Greenhouse effects causing substances
    - Methane (CH_4), nitrous oxide (N_2O), carbon tetra-fluoride (CF_4) etc.
  - Based on life cycle assessment (LCA)
  - ISO 14040 and ISO 14044



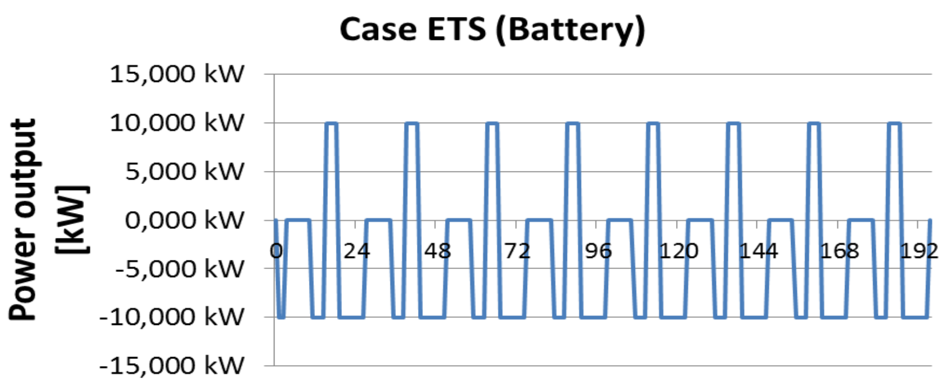
Energy Storage Benchmarking Methodology LCA und LCC



Energy Storage Benchmarking: Use cases

Karlsruher Institut für Technologie

- Electric time shift (ETS)
  - Energy/Power = 4
  - 10 MW/40 MWh
- PV self-consumption PVSC
  - Energy/Power = 3.2
  - 2.5 kW / 8 kWh
- PR Primary regulation
  - Energy/Power = 1
  - 1MW / 1 MWh
- RS Renewables support:
  - Energy/Power =10
  - 2MW / 20 MWh



ETS: Energy is stored when RES produce excess electricity and dispatched during high demand times.

PVSC: Energy storage used by end-use customers to reduce their electricity bill by storing the energy

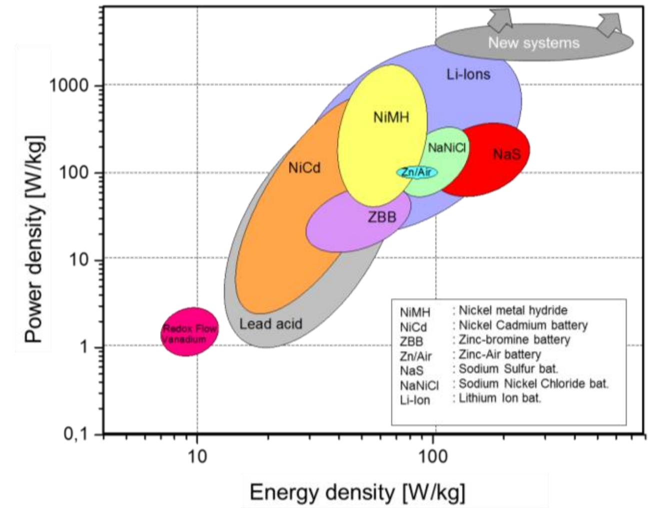
PR: Measures for short time reconciliation of supply and demand

RS: Energy stored in periods of low electricity prices and dis-charged during times of high prices

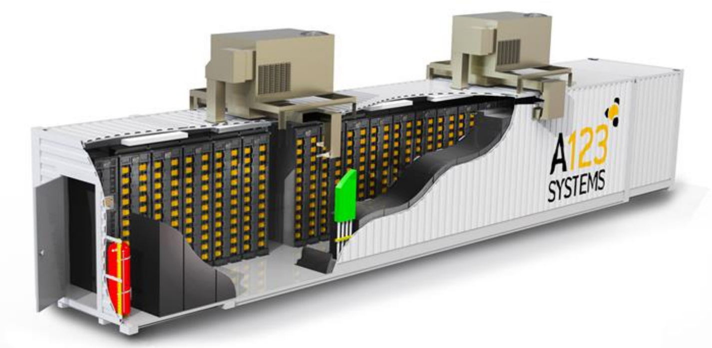
Energy Storage Benchmarking: Electrochemical Energy Storage Technologies

Karlsruher Institut für Technologie

- **LFP** li-iron-phosphate / graphite anode
- **LTO** li-iron-phosphate / lithium-titanate anode
- **NCM** li-ni-cobalt-mg-oxide / graphite anode
- **NCA** li-ni-cobalt-aluminum-oxide / graphite anode
- **LMO** li-mg-oxide / graphite anode



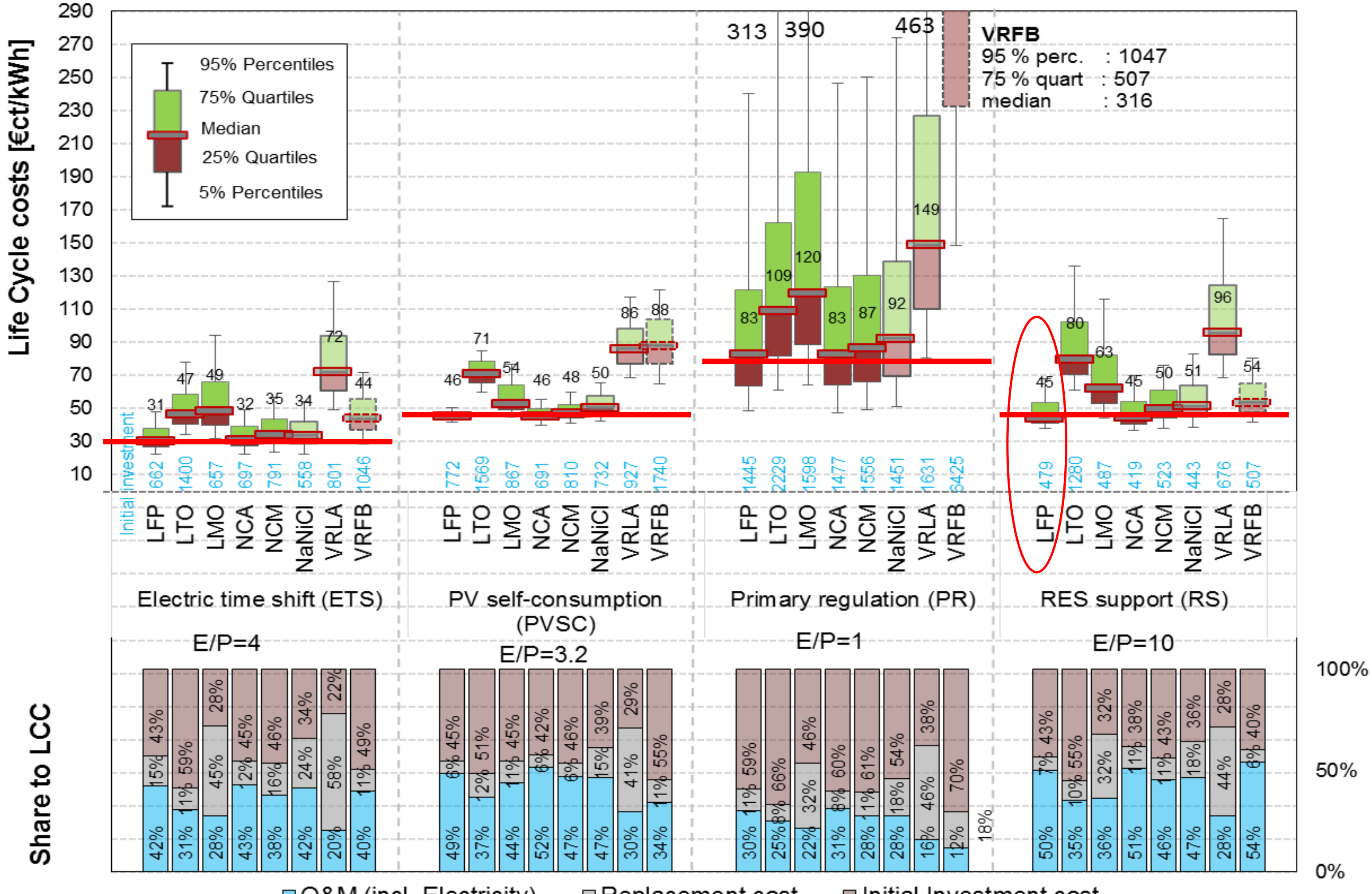
- **NaNiCl** sodium-nickel-chloride battery
- **VRFB** vanadium redox flow battery
- **VRLA** valve regulated lead acid



http://www.altenergymag.com/images/upload/images/A123%20Systems%20energy%20storage%20system%20cutaway.jpg

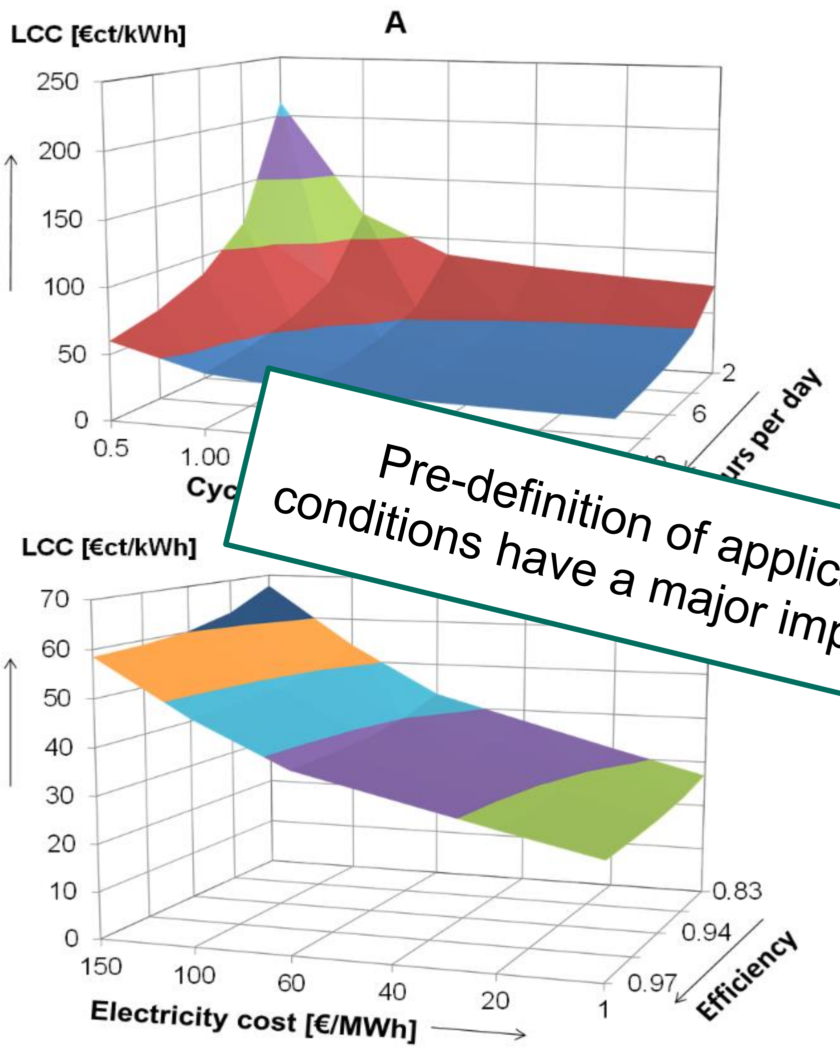
Costs

Energy Storage benchmarking: Life Cycle Costing



Source: Baumann et al. 2017

Sensitivity analysis:
Life Cycle Costing



A)
operation conditions including number of cycles and charging time per cycle

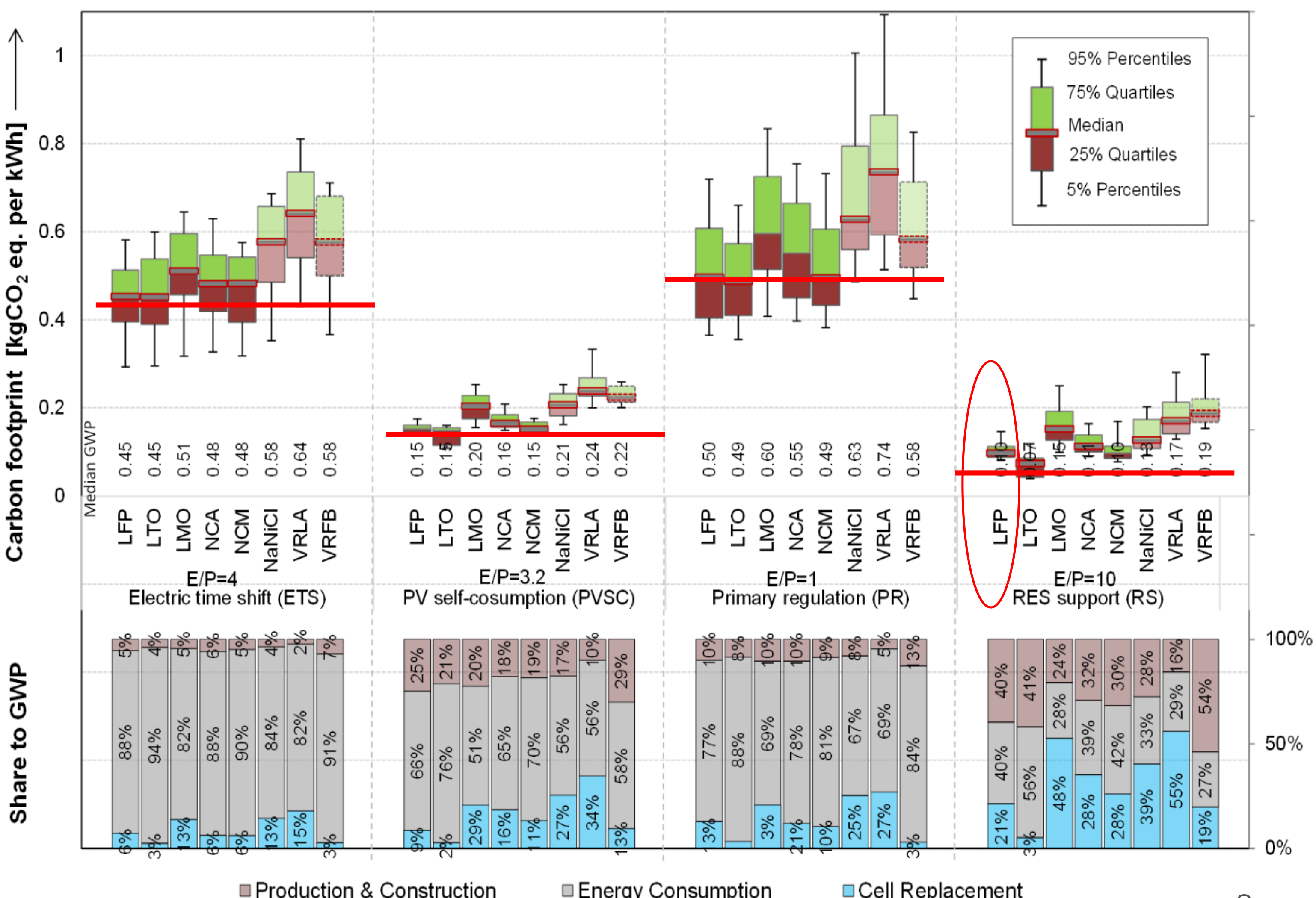
Pre-definition of application requirements & market conditions have a major impact on overall cost performance

purchased electr

Source: Baumann et al. 2017

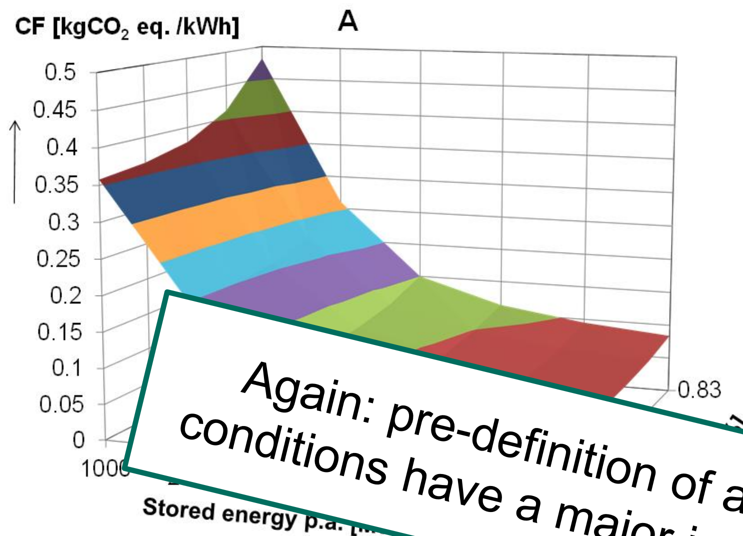
Global Warming Potential GWP

Energy Storage Benchmarking:
Carbon Footprint / Global Warming Potential



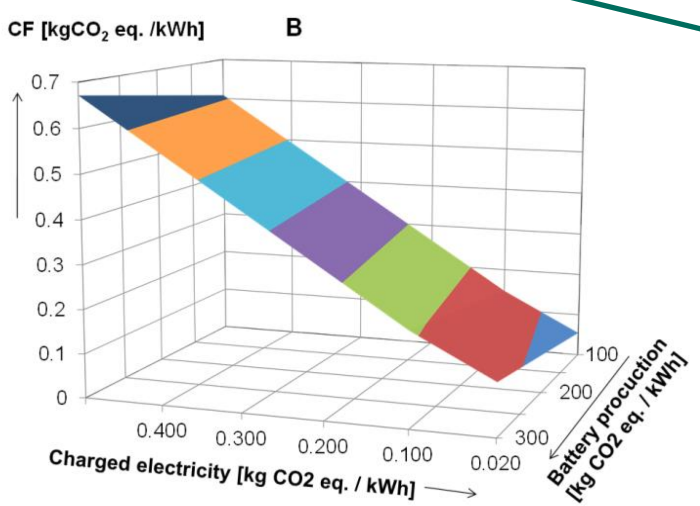
Source: Baumann et al. 2017

Sensitivity analysis: Carbon Footprint



A)
Variation of efficiency and total stored energy per year

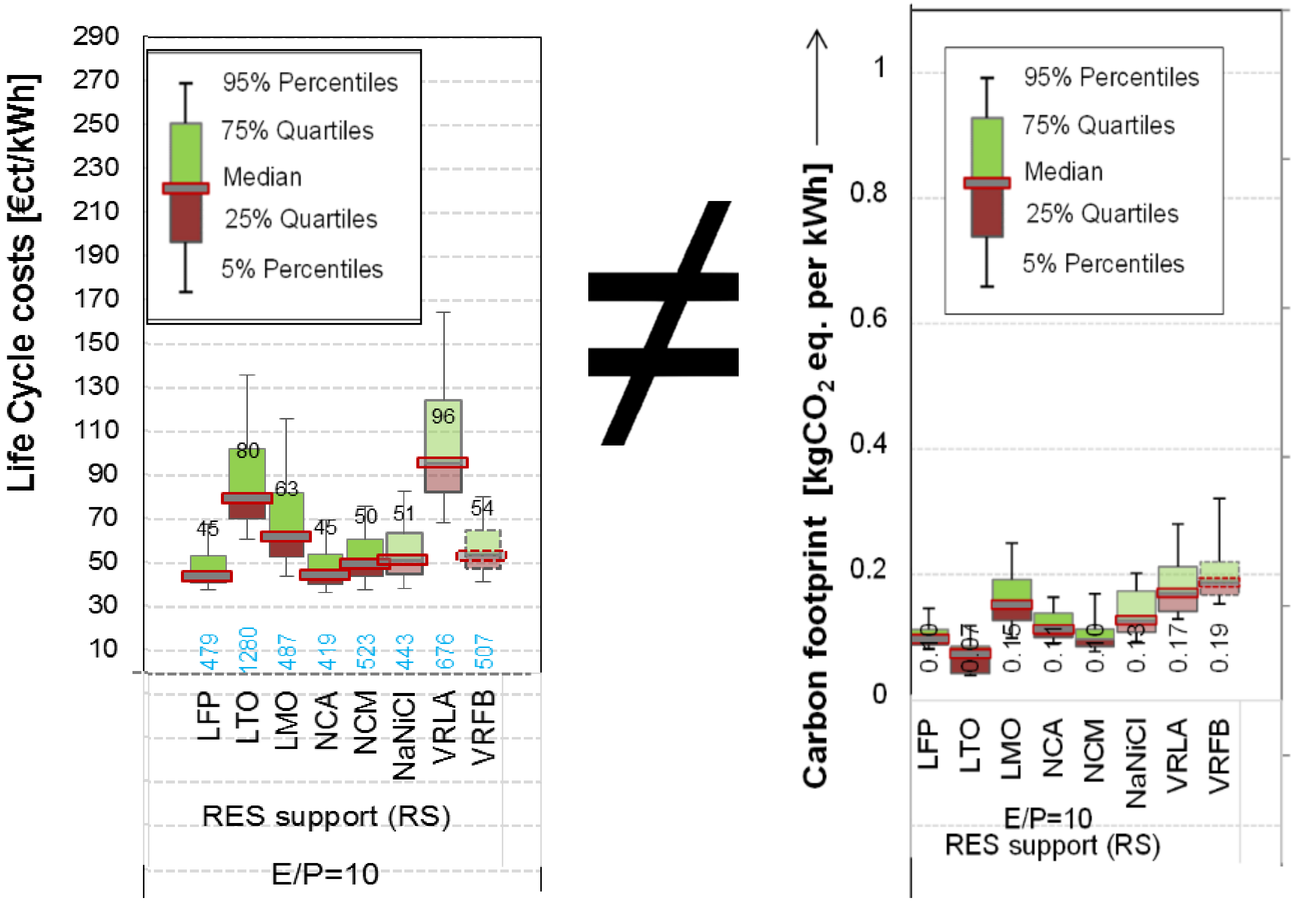
Again: pre-definition of application requirements & market conditions have a major impact on environmental performance



B)
battery production vs. charged electricity

Source: Baumann et al. 2017

Energy Storage Benchmarking
LCC vs. Carbon Footprint



- Different Benchmark metrics might lead to conflicting results

Source: Baumann et al. 2017

Benchmarking Hybrid Energy Storage Technologies: LIQHYSMES

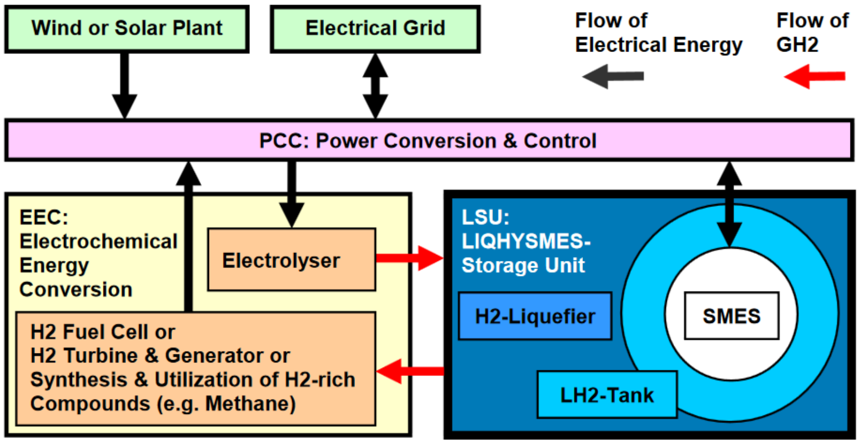
- Hybrid energy storage → combination of complementary technologies
  - Fuel cells+batteries, SuperCaps+Lead acid etc.

- Liquid hydrogen (LH_2) with Superconducting Magnetic Energy Storage (SMES)

- LH2 High vol. energy density 20 – 40 kg/m³ @ 350 – 700 bar

- Operated with SMES (e.g. MgB2) high temp. Superconducter in LH_2 bath @ 20 K / ø 30 m ~ 60 GWh

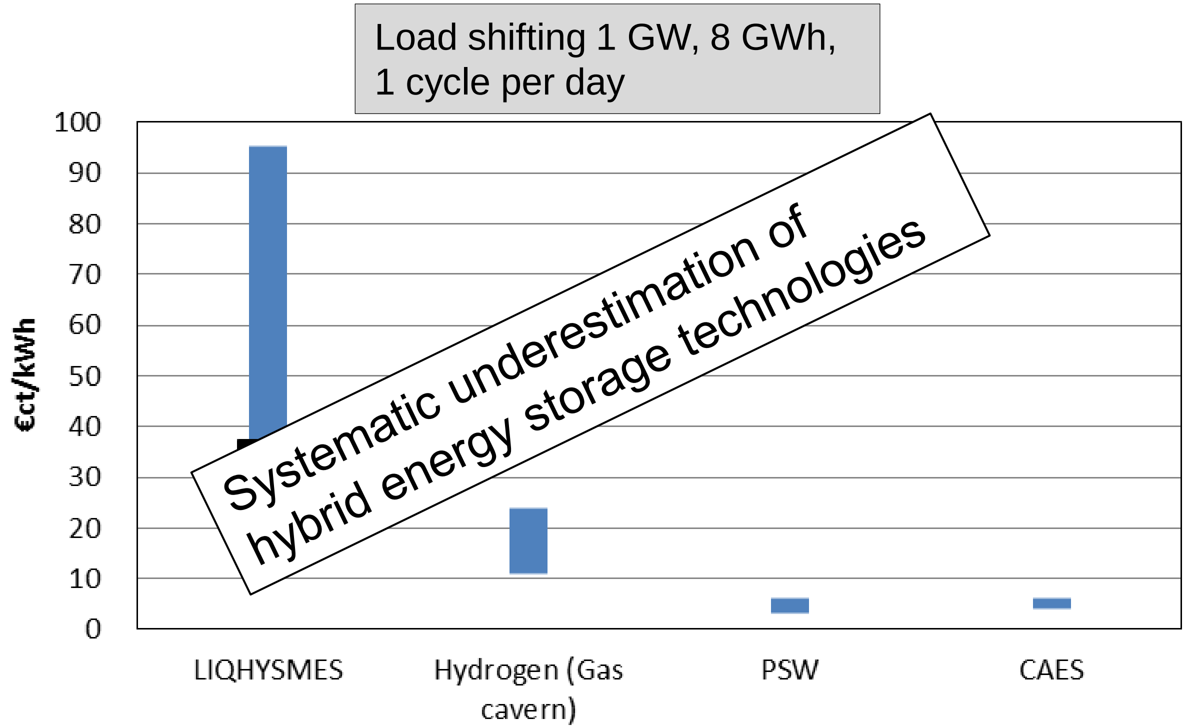
- Maturity level – very low



Sander et. al 2014

Benchmarking Hybrid Energy Storage Technologies: LIQHYSMES

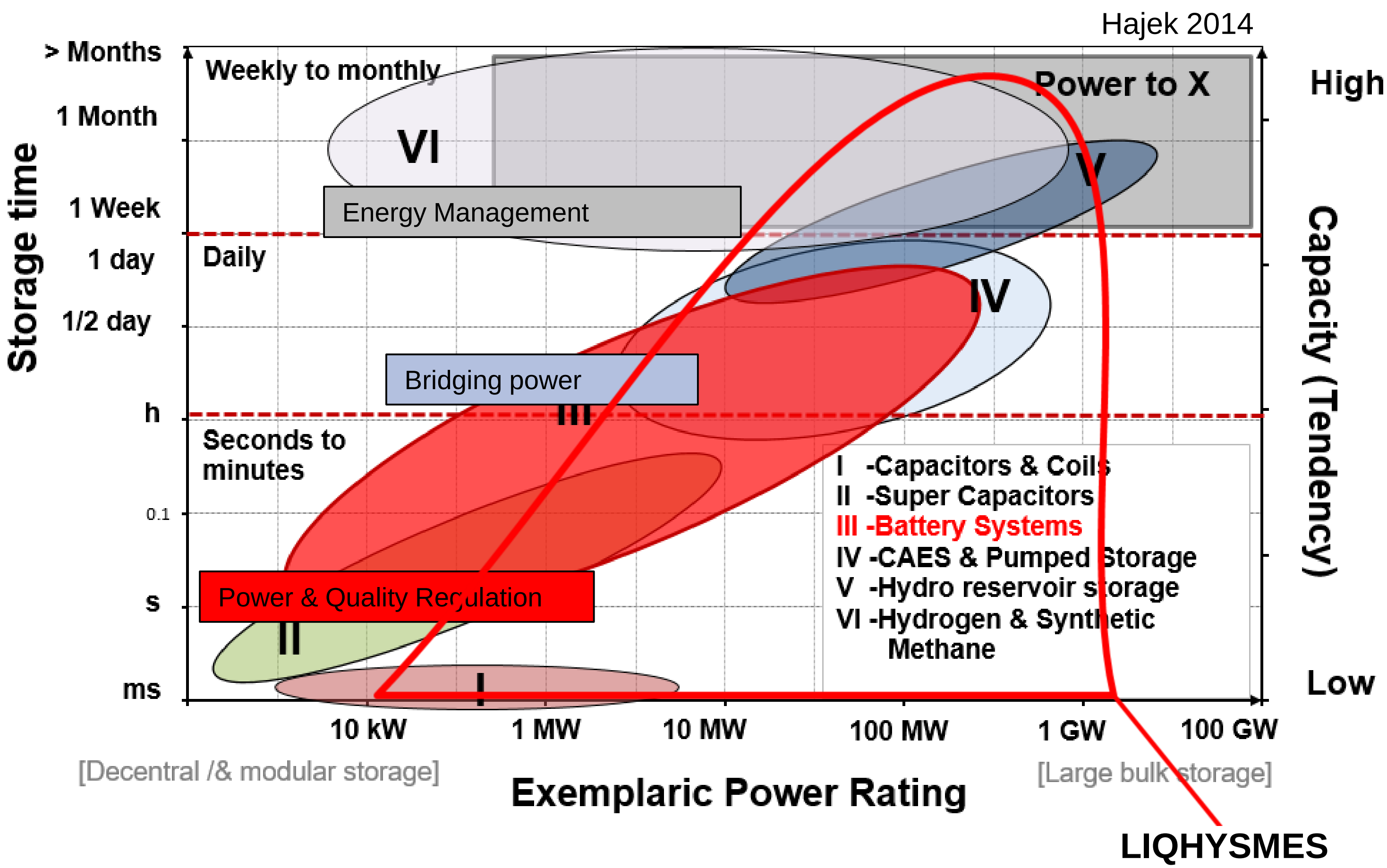
- Comparison of LCC of LIQHYSMES, H2, PHS and CAES for load shifting



Hajek 2014

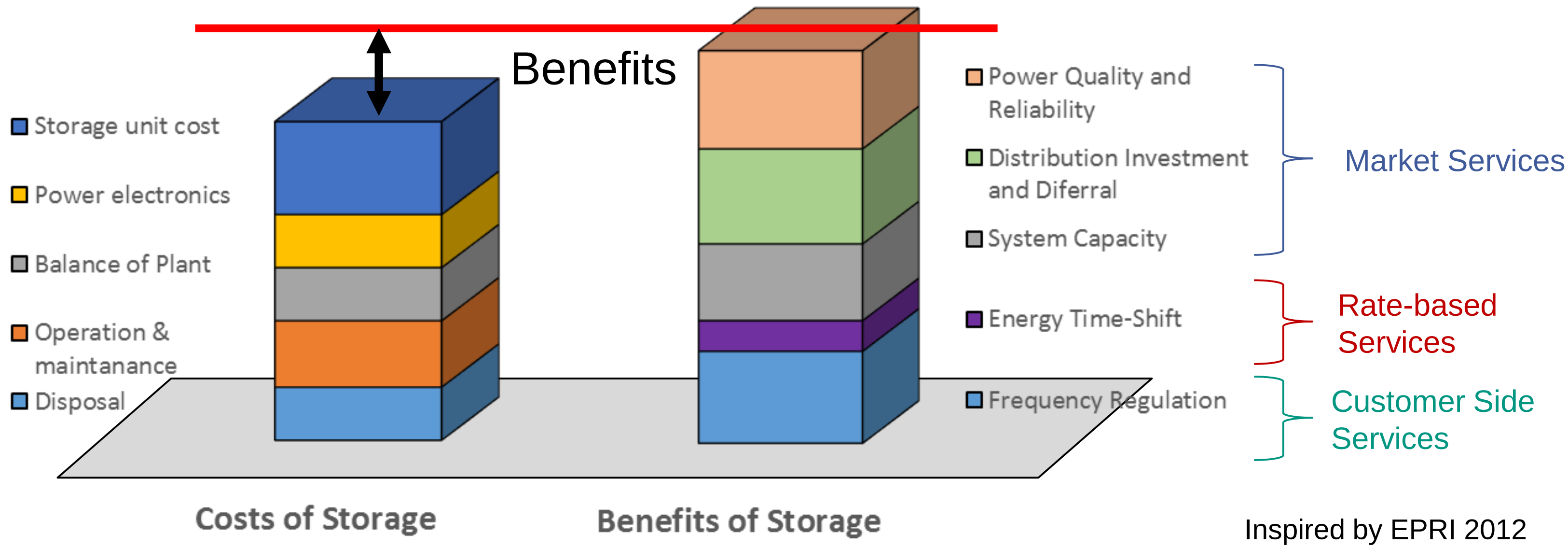
- LIQHYSMES is only hardly competitive in this certain application
- Low maturity level leads to high uncertainty of results (e.g. PHS vs. LIQHYSMES?) due to limited availability of data

Benchmarking Hybrid Energy Storage Technologies: LIQHYSMES



LIQHYSMES is able to cover a wide range of applications

Benchmarking Hybrid Energy Storage Technologies: Cost Vs. Benefits



Inspired by EPRI 2012

- Costs only provide one side of the coin
- **Stacking** of services, aggregation of complementary benefits through the provision of multiple services might outweigh cost
- High potential especially for hybrid Energy Storage technologies

Summary

- Different application areas –> requirements have to be defined
- Storage technology properties have to be matched with application requirements
- Several indicators available for benchmarking
- Benchmarking with LCC & GWP → potentially conflicting results
  - Potential solutions are e.g. Multi-Criteria Decision Analysis
- Hybrid technologies are able to cover various application areas
  - Proper application fields/ business cases have to be defined
  - Availability of robust data is a challenge

Key questions for further discussion

1. How can **energy technologies** be benchmarked considering their **specific properties** in face of **different grid needs?**

2. How to define **suitable application cases** for single and especially hybrid energy storage technology benchmarking?

Where to find us

ITAS

Institute for Technology Analysis and System Analysis
Karlstraße 11, Karlsruhe
Germany
http://www.itas.kit.edu/

Research area Innovation processes and impacts of technology

Manuel Baumann
Manuel.baumann@kit.edu

Marcel Weil
Marcel.weil@kit.edu

Jens Peters
Jens.peters2@kit.edu

Literature

- M. Sander 2014; LIQHYSMES – a Novel Hybrid Energy Storage Option for Buffering Short- & Long-Term Imbalances between Electricity Supply & Load; https://indico.psi.ch/getFile.py/access?resId=0&materialId=slides&confId=2191
- M. Hajek, 2014, Analyse potentieller Einsatzbereiche von LIQHYSMES im deutschen Stromnetz, Bachelor thesis, technische Hochschule Ingolstadt
- Baumann, M.; Peters, J.; Weil, M.; Grunwald, A. CO_2 footprint and life cycle costs of electrochemical energy storage for stationary grid applications. Energy Technology - Generation, Conversion, Storage, Distribution 2017, DOI: 10.1002/ente.201600622
- D. Mooney, 2015, Large-Scale Energy Storage, GCEP Tutorial Series, NREL
- IEC, 2011, Electrical Energy Storage - White paper, ISBN 978-2-88912-889-1
- Sauer, U. (09. Februar 2010). *Energiespeicher für ein stabiles Netz*. Abgerufen am 28. Juli 2011 von http://www.cef.nrw.de/_database/_data/data-infopool/FK2010-E-Sauer.pdf

Major techno-economic inputs for cells

Table 1. Key performance parameters of the assessed batteries using upper quartiles, median and lower quartile values based on available recent literature and industry data sources from the Batt-DB [7], [16], [17] using the most recent (complete) datasets as indicated in the second row for each technology

Component	Unit	Range	VRLA	LTO	LFP	LMO	NMC	NCA	NaNiCl	VRFB
Oldest source used from Batt-DB			2013	2013	2013	2013	2013	2013	2012	2010
Cost	€/kWh	min 75 q	169	600	289	153	192	172	86	129
		median	230	900	309	238	318	213	220	458
		max 25 q	320	1200	315	564	554	355	403	860
Cycle lifetime @ DoD[a] 80 %	-	min 75 q	300	4500	1750	1000	1000	1250	1000	9000
		median	1400	8000	5000	1500	4000	3000	3000	10000
		max 25 q	1600	9750	5325	5000	4875	5125	6250	13250
Efficiency	% DC-DC	min 75 q	63	81	83	85	83	90	84.25	65
		median	76.5	90	96	94	93.8	91.55	86	75
		max 25 q	90	94.5	96.5	98.25	97.275	93.1	91.25	85
Calendric Lifetime	a	min 75 q	10	10	7.5	5	5	10	10	6.25
		median	18.0	17.5	15.0	10.0	10.0	10.0	14.0	15.0
		max 25 q	20.0	25.0	20.0	15.0	15.0	15.0	14.8	20.0
O&M[b] cost	€/kW y	min 75 q	4.3	11.0	17.0	20.0	20.0	20.0	12.4	17.7
		median	16.9	25.0	25.0	25.0	20.0	25.0	20.9	40.0
		max 25 q	37.4	33.8	31.3	30.0	30.0	30.0	44.8	50.5

[a] DoD=Depth of Discharge
[b] O&M=Operation and maintenance

Source: Baumann et al. 2017

Major techno-economic inputs for system

Karlsruher Institut für Technologie

Table S1. Cost assumptions (first year) obtained from literature. BMS = battery management system; BOS=Balance of system

Type	Cost €/kW	Comment	Source
Contingency	83	Covers unforseeable events	[12]
Installation	~125		[12], [16]
BMS+BOS	273 - 475	Missing common definition	[12], [16], [2]
Enclosure	~10	Dependent on technology	[12]
Inverter	-	Depends on scale effects	[13], [2]
Utility Intercon. Eq.	~59	Can vary extremely	[12]
Battery	see table X	Technology dependent	Batt-DB
Interconnection eq.	~59	Dependent from location	[12]
Permitting	~50	Dependent of region	[16]

Source: Baumann et al. 2017

LCA sources

Karlsruher Institut für Technologie

Table 4. CO_2 footprint of battery production as calculated based on corresponding LCI source

Technology	$kgCO_2/kg$	Wh/kg	$kgCO_2/kWh$	Source
LFP	16.11 13.98	109 83	147.41 168.56	[50], [51], [49]
LTO	14.19	52	270.99	[49], [52]
LMO	13.80	116	118.90	[49], [53]
NCM	14.12 16.13	130 139	108.30 115.98	[54], [50], [49]
NCA	15.40	133	115.74	[49], [52]
VRLA	2.33	45	51.60	[55]
NaNiCl	13.01	112	116	[56], [57], [58]
VRFB	3.20	17	183	[45], [59]

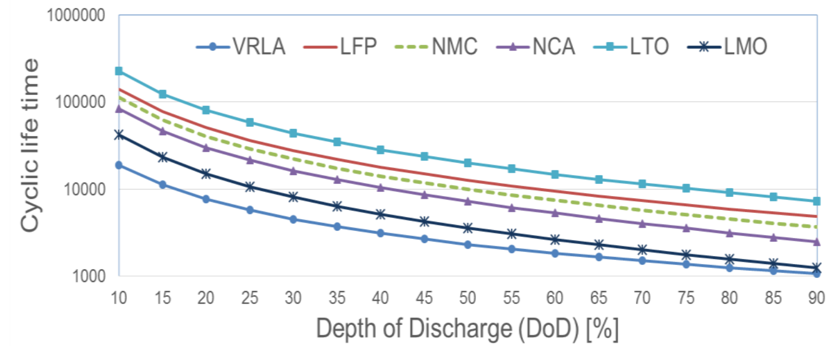
Source: Baumann et al. 2017

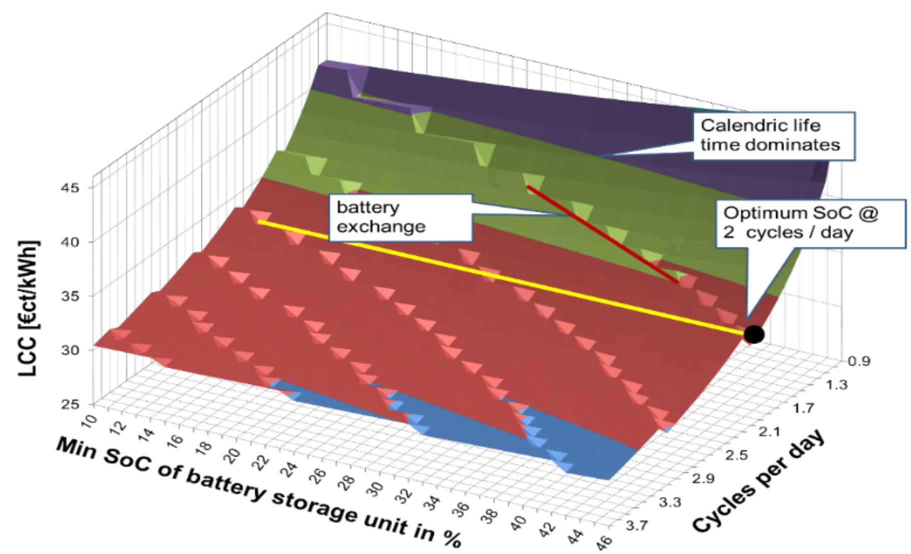
SoC-Optimization

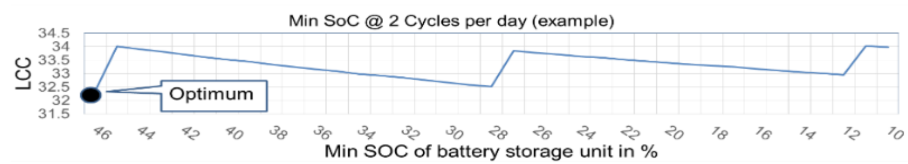
- Based on energy storage data-base
- Fitting curves to these data
- Optimum ration between exchanges & total cost over life-time

- Only available for LIBs and VRLA

- NaNiCl and NaS to be tested







Source: Baumann et al. 2017

SoC-Optimization

Karlsruher Institut für Technologie

Table 5. Median values of SoC optimization, resulting storage capacity and number of replacements

Application		LFP	LTO	LMO	NCA	NCM	NaNiCl	VRLA	VRFB
ETS	minSoC %	23	10	30	46	34	20	44	20
	Nom Size MWh	57	52	64	85	68	61	99	70
	Replacements	1	1	4	1	2	4	6	1
PVSC	minSoC %	10	10	37	12	10	20	39	20
	Nom Size MWh	0.010	0.010	0.014	0.011	0.010	0.012	0.018	0.014
	Replacement	1	1[a]	1	1	1	2	4	1[a]
PR.	minSoC %	12	10	44	38	25	20	44	20
	Nom Size MWhC	1.3	1.3	2.0	1.9	1.5	1.8	2.4	1.8
	Replacement	2	1	4	2	2	3	6	1
RS	minSoC %	10	10	22	19	10	20	44	20
	Nom Size MWh	24	26	29	28	25	31	49	35
	Replacement	1	1[a]	3	1	1	2	4	1[a]

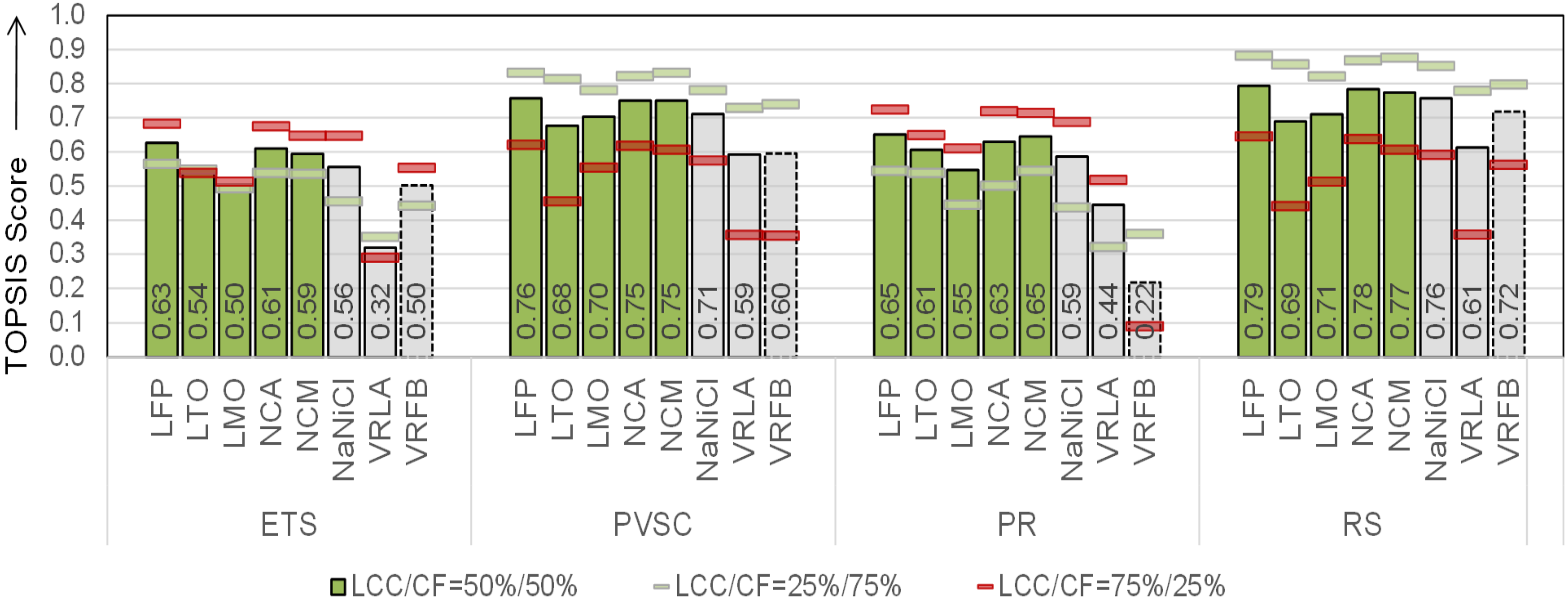
[a] Battery exchange due to insufficient calendric life time

Source: Baumann et al. 2017

MCDA – CF vs. LCC

Karlsruher Institut für Technologie

- Technique for Order Preference by Similarity to Ideal Solution



Source: Baumann et al. 2017