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

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Introduction

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

**A** "Short term storage" $4 < x < 5$ h

**B** "Mid term storage" $8 < x < 10$ h

\[ y = 0.0073x^2 - 29.662x + 29063 \]

\[ y = 0.0134x^2 - 54.313x + 54666 \]
Introduction

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

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Exemplaric Power Rating

Inspired by Sauer et. al 2010
## Introduction

- Multiple application fields → each with specific requirements

<table>
<thead>
<tr>
<th>Cycles per use</th>
<th>Duration of cycles</th>
<th>0.1 s</th>
<th>15 s</th>
<th>15 min</th>
<th>1 h</th>
<th>8 h</th>
<th>days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30/h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Bridging power**
  - Spinning reserves, ramping, load following etc.

- **Energy Management**
  - Defer up-grades, price arbitrage etc.

- **Power & Quality Regulation**
  - Maintain power quality, Def er system Inertia etc.

### P&Q - Regulation
- **Response time**
- Cycles / cost
- ...

### Energy management
- **Cycles / costs**
- Response time
- ...

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Inspired by IEC 2011
Benchmarking Energy Storage: General approach

1. Relevant Technology
2. Energy storage characteristics
3. Application field / Business case definition/requirements
4. Performance metrics / Benchmark

A
- Time resolution
- Cycles
- DoDs
- Response time

B
- Efficiency
- Investment cost
- Cycle life time etc.
- xxx

x

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 kgCO₂ 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$_2$O), carbon tetra-fluoride (CF$_4$) etc.
  - Based on life cycle assessment (LCA)
  - ISO 14040 and ISO 14044
Energy Storage Benchmarking
Methodology LCA und LCC

**Input data**

- **Techno-econ. inputs:** Batt-DB with 28 data categories; >5000 data points
- **Application field data:** different load profiles from literature & own calculations
- **LCA-input:** Comprehensive literature review + techno-economic data and operation data

**Economic Calculus (EC)**

- Deterministic LCC Calculation
- Scale & learning curve effects
- Optimization of battery capacity
- Probabilistic calculation
- Inputs: Cycles, €/kWh, Balance of plant cost, efficiency, power conversion system cost, calendric life time, charging & disch. duration, el. price, operation and maintenance cost

**Carbon Footprint**

- Life cycle inventory (ecoinvent 3.2 database)
- LCA results / Carbon footprint
- Probabilistic calculation
- Inputs: Battery size, charging & dis-charging duration, impact per kWh, battery ex-changements over life time

**Benchmarking**

- LCC €/kWh
- GWP kgCO2-eq./kWh
Energy Storage Benchmarking: Use cases

- 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

**Case ETS (Battery)**

**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 discharged during times of high prices
Energy Storage Benchmarking: Electrochemical Energy Storage Technologies

- **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

Costs
Energy Storage benchmarking: Life Cycle Costing

![Graph showing Energy Storage benchmarking results]

- **Life Cycle costs [€/kWh]**
  - 95% Percentiles
  - 75% Quartiles
  - Median
  - 25% Quartiles
  - 5% Percentiles

### Electric time shift (ETS)

- E/P=4
- E/P=3.2

### PV self-consumption (PVSC)

- E/P=1

### Primary regulation (PR)

- E/P=10

### RES support (RS)

- **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 and purchased electricity.

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)

- LH$_2$ High vol. energy density
  20 – 40 kg/m$^3$ @ 350 – 700 bar

- Operated with SMES (e.g. MgB2) high temp. Superconductor 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

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.
 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**
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[http://www.itas.kit.edu/](http://www.itas.kit.edu/)

Research area Innovation processes and impacts of technology

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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


D. Mooney, 2015, Large-Scale Energy Storage, GCEP Tutorial Series, NREL


# 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.

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

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

Source: Baumann et al. 2017
## Major techno-economic inputs for system

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

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

Source: Baumann et al. 2017
## LCA sources

Table 4. CO₂ footprint of battery production as calculated based on corresponding LCI source

<table>
<thead>
<tr>
<th>Technology</th>
<th>kgCO₂/kg</th>
<th>Wh/kg</th>
<th>kgCO₂/kWh</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>LFP</td>
<td>16.11</td>
<td>109</td>
<td>147.41</td>
<td>[50],</td>
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<td></td>
<td>13.98</td>
<td>83</td>
<td>168.56</td>
<td>[51],</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[49]</td>
</tr>
<tr>
<td>LTO</td>
<td>14.19</td>
<td>52</td>
<td>270.99</td>
<td>[49],</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>[52]</td>
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<td>LMO</td>
<td>13.80</td>
<td>116</td>
<td>118.90</td>
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<td>[53]</td>
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<tr>
<td>NCM</td>
<td>14.12</td>
<td>130</td>
<td>108.30</td>
<td>[54],</td>
</tr>
<tr>
<td></td>
<td>16.13</td>
<td>139</td>
<td>115.98</td>
<td>[50],</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>[49]</td>
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<tr>
<td>NCA</td>
<td>15.40</td>
<td>133</td>
<td>115.74</td>
<td>[49],</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>[52]</td>
</tr>
<tr>
<td>VRLA</td>
<td>2.33</td>
<td>45</td>
<td>51.60</td>
<td>[55]</td>
</tr>
<tr>
<td>NaNiCl</td>
<td>13.01</td>
<td>112</td>
<td>116</td>
<td>[56],</td>
</tr>
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<td></td>
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<td></td>
<td>[57],</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[58]</td>
</tr>
<tr>
<td>VRFB</td>
<td>3.20</td>
<td>17</td>
<td>183</td>
<td>[45],</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[59]</td>
</tr>
</tbody>
</table>

Source: Baumann et al. 2017
SoC-Optimization

- Based on energy storage database
- 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

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

<table>
<thead>
<tr>
<th>Application</th>
<th>LFP</th>
<th>LTO</th>
<th>LMO</th>
<th>NCA</th>
<th>NCM</th>
<th>NaNiCl</th>
<th>VRLA</th>
<th>VRFB</th>
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<tbody>
<tr>
<td>ETS</td>
<td>23</td>
<td>10</td>
<td>30</td>
<td>46</td>
<td>34</td>
<td>20</td>
<td>44</td>
<td>20</td>
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<tr>
<td></td>
<td>57</td>
<td>52</td>
<td>64</td>
<td>85</td>
<td>68</td>
<td>61</td>
<td>99</td>
<td>70</td>
</tr>
<tr>
<td>Replacements</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>PVSC</td>
<td>10</td>
<td>10</td>
<td>37</td>
<td>12</td>
<td>10</td>
<td>20</td>
<td>39</td>
<td>20</td>
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<tr>
<td></td>
<td>0.010</td>
<td>0.010</td>
<td>0.014</td>
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<td>0.010</td>
<td>0.012</td>
<td>0.018</td>
<td>0.014</td>
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<tr>
<td>Replacement</td>
<td>1</td>
<td>1[a]</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>1[a]</td>
</tr>
<tr>
<td>PR.</td>
<td>12</td>
<td>10</td>
<td>44</td>
<td>38</td>
<td>25</td>
<td>20</td>
<td>44</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>1.3</td>
<td>2.0</td>
<td>1.9</td>
<td>1.5</td>
<td>1.8</td>
<td>2.4</td>
<td>1.8</td>
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<tr>
<td>Replacement</td>
<td>2</td>
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<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>RS</td>
<td>10</td>
<td>10</td>
<td>22</td>
<td>19</td>
<td>10</td>
<td>20</td>
<td>44</td>
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<td>24</td>
<td>26</td>
<td>29</td>
<td>28</td>
<td>25</td>
<td>31</td>
<td>49</td>
<td>35</td>
</tr>
<tr>
<td>Replacement</td>
<td>1</td>
<td>1[a]</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>1[a]</td>
</tr>
</tbody>
</table>

[a] Battery exchange due to insufficient calendric life time

Source: Baumann et al. 2017
MCDA – CF vs. LCC

- Technique for Order Preference by Similarity to Ideal Solution

Source: Baumann et al. 2017