Energy Storage Technologies
Battery Storage for Grid Stabilization

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Electrochemical Energy Conversion and Storage Systems (ISEA)
Who we are

- RWTH Aachen University
  - Major technical university in Germany, >30,000 students
  - Electrical Power Engineering: 5 institutes / 6 professors, >250 PhD candidates
  - Biggest research cluster on electrical energy technology in Germany

- Storage @ Aachen University
  - Electrical Engineering: from cell - to system - to application - to techno-economics
### Chair for Electrical storage systems

<table>
<thead>
<tr>
<th>Role</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professor</td>
<td>1</td>
</tr>
<tr>
<td>Senior scientists / heads of section</td>
<td>3</td>
</tr>
<tr>
<td>Scientist and engineers</td>
<td>65</td>
</tr>
<tr>
<td>Research fellows</td>
<td>5</td>
</tr>
<tr>
<td>Students (full and part time)</td>
<td>60+</td>
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</tbody>
</table>

### Electrical storage systems

- Lead Acid, Li-Ion, NiMH, NiCd, SuperCaps, Fuel Cells, Redox-Flow and others ...
- Energy- und Battery Management Systems
- Thermal and electrical modelling
- Battery pack design
- Characterization and durability tests
- System integration renewable energy
- Hybrid, plug-in und electric vehicles
- Vehicle power net
- Micro grids / Autonomous power systems
- Uninterruptible power supply (UPS)
Electricity price / PV-cost opens window for storage
- Depends on cost of generation, electricity and storage (and regulation!)
- Sizing + energy management determine viability
Massive decay of prices for lithium-ion-cells

Electric mobility dominates development (> ten-fold market size of stationary)

Drives also stationary storage system costs down (in part)
Motivation 3
Renewables: Where do we need storage?

50 Hertz Transmission (Februar 2008)

Prognosis uncertainty
System stability

Flexible convention. generation !
(up to 60% FRE)

Load Wind generation (real)
Wind generation (prognosis)
Storage Applications

Source: IfR / TU Braunschweig

Pumped Hydro Capacity in Germany
40 GWh, 5GW

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Motivation 4
Batteries in Electric Vehicles

Total power rating and storage capacity
2020: 1 million EV = 3 GW / 10-20 GWh
Selected Projects

- WMEP
  - Scientific Monitoring and Evaluation Program of the Market Incentive Program for PV-Storage Systems

- GENESYS
  - Genetic Optimization of the European Energy System

- Battery Storage for Grid Stabilization
  - M5Bat: Modular Multi-Megawatt Multi-Technology Medium Voltage Battery
Goal: Determination of the cost optimal European Energy System with 100% Renewable Energy

- Optimization for minimal cost
- Simulation of 100% renewables for entire Europe, 7 years of data, 1h resolution
- Estimate of required capacities of generators (PV and wind) different storage types and grid
- Simplified model for fast analysis of multiple years of data. General picture plus sensitivities. 30 regions plus interconnections
GENESYS Result 1: Genetic Optimization of the European Energy Systems

- **Long Term Storage** 802,000 GWh
  - Technology: Power to Gas
  - Charge/Discharge: 880 / 540 GW
  - Energy/Power Ratio: Ø1270 h

- **Medium Term Storage** 2,730 GWh
  - Technology: Pumped hydro
  - Charge/Discharge: 190 GW
  - Energy/Power Ratio: Ø 15 h

- **Short Term Storage** 1,550 GWh
  - Technology: Battery Storage
  - Charge/Discharge: 320 GW
  - Energy/Power Ratio: Ø 6 h

Total Discharge Power ~ Peak Demand
At 100% RE only fixed costs i.e. CAPEX plus maintenance

Cost per kWh dominated by CAPEX of generation capacity (wind and photovoltaics)

Fraction of storage systems about 25% of total system cost

Transmission grid contributing just below 10%
The M5BAT Project

Modular Multi-Megawatt Multi-Technology Medium Voltage Battery
Partners

+ RWTH Aachen University (Project Lead)
  + PGS (Batterie research)
  + EBC (Building monitoring)
  + IAEW (Energy Economics)

+ beta-motion GmbH (Li-Ion Battery)

+ E.ON SE (Building, Marketing)

+ GNB Industrial Power – Exide Technologies (Lead Acid Battery)

+ SMA Solar Technology AG (Inverter)
M5BAT – Projekt Overview

+ Projekt duration: 4 years (07/2013-06/2017)
+ Planing and construction: 2 years
+ Operation: 2 years
+ Total Budget: 12,5 Mio. Euro
+ Funding BMWi: 6,5 Mio. Euro

+ Projekt goals:
  + Construction of a pilot hybrid battery storage system
  + Realistic operation and market participation in several applications
    + E.g. Primary Control Reserve, SRL, MR, Arbitrage, Ramping support …
  + Evaluation of technical and economical results and development of recommendations for design and operation of hybrid battery systems
  + Development of several components for Battery Storage Systems
    + System Control and Monitoring System (Leittechnik, Anlagensteuerung)
    + Optimized design for stationary lead acid batteries
    + Optimized control for inverters
M5BAT – Timeline

- Project duration: 4 years (07/2013 – 06/2017)
  - Planning, permissions, detail planning, tenders
  - Retrofit of existing building
  - Installation of components (batteries, inverter, TGA, electrical system, protection and control system)
  - Operation and evaluation

TGA = Technische Gebäude-Ausrüstung
M5BAT – Technical Data

+ 5 parallel strings (voltage level between 450-820 V DC)
+ Nominal power rating: 5 MW (AC) / overall capacity: 4,2 MWh
+ 2 parallel inverters per string à 630 kVA nominal power
**Batterien – Technical Data**

+ Each string connected with two inverters (2-4 parallel inverters à 630 kVA)
+ Separate control für each string possible

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Power / Capacity</th>
<th>Manufacturer</th>
</tr>
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<tbody>
<tr>
<td>Lead-Acid(OCSM)</td>
<td>1,25 MW / 1,48 MWh</td>
<td>GNB Industrial Power (Partner)</td>
</tr>
<tr>
<td>VRLA Lead-Acid(OPzV)</td>
<td>0,85 MW / 0,85 MWh</td>
<td>GNB Industrial Power (Partner)</td>
</tr>
<tr>
<td>Lithium-Ion (NMC)</td>
<td>2,50 MW / 0,77 MWh</td>
<td>beta-motion (Partner)</td>
</tr>
<tr>
<td>Lithium-Ion (LFP, LTO or LMO )</td>
<td>1,25 MW / 0,6 MWh</td>
<td>Tendered</td>
</tr>
<tr>
<td>NaNiCl</td>
<td>0,25 MW / 0,5 MWh</td>
<td>Tendered</td>
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Capacity at 1h discharge (C1)
Usable capacity of lead acid batteries is larger at slower discharge
VRLA = Valve Regulated Lead Acid
M5Bat - Goals

Deliverables

+ Handbook for design and operation of MW-Battery Systems in MV-grid
+ Technology comparison, single and combined operation
+ Delivery of multiple services (revenue stacking)
+ Grid planning and operation implications

RWTH Aachen-IAEW und RWTH Aachen-PGS
M5Bat - Impressions
Primary Control Reserve

- Pay as bid auction by TSO: weekly, min bid 1 MW
- Participation requires prequalification
- Activation fully automatic based on grid frequency (static)
- Market volume 570 MW in Germany (100 M€/a), 3.000MW in Europe

Coupled Markets:
- 25 MW CH
- 35 MW NL

Source: www.regelleistung.net
Primary Control Reserve (PCR) – Load Profile
Primary Control Reserve (PCR) – Load Profile

- 72% of the time no load (dead band)
- Activation nearly symmetrical pos. and neg. reserve – not quite
- Maximum demand in 3 months 70% of nominal power rating
  - Activation of > 25% of nominal power in 0.36% of the time → 15.4 hours per year
  - Activation of > 50% of nominal power in 0.0036% of the time → 8.5 minutes per year
Li-Ionen Batteries - Aging

+ Lifetime: superposition of calendaric and cyclic aging
+ To first order
  + Low SOC → longer life / high SOC → shorter life
  + Low delta SOC → longer life / high delta SOC → shorter life.
Primary Control Reserve (PCR) – SOC Profile

+ Operational strategy for compensation of losses necessary (slow and low power)
+ Time share at given SOC depends on size of battery – influence on aging
+ Smaller capacity results in larger variation of SOC i.e. increased aging
+ String influence on invest (capex)
+ Prequalification requires 2 x 15 min full load, ENTSOE pushing towards 2 x 30 min
+ Technically 0.5 MWh/MW sufficient – only prequalification requires 1MWh/MW
M5Bat – Lessons learned so far

+ Safety standards for LIB-systems missing – no reference cases
  ➔ permissions difficult (fire, hazard, explosion, earthquake)
  ➔ safety levels of car industry not applicable
    (e.g. controlled burn down not feasible)
  ➔ explosion of single cell less critical than explosion of aerosols

+ Grid connection fees even though system operated exclusively for grid services: 60 T€ per MW = 6 % of invest

+ Tender very complex - without references no established warranty schemes

+ Time line very slow due to lack of experience at many stakeholders (administration, municipality, fire department, …)

+ No standard for prequalification, back up, penalties
  ➔ individual negotiations with TSO necessary
Questions

- Which energy storage technologies are currently used?
- What is the status of these technologies? Can they be scaled?
- Which primary technological limitations and barriers need to be overcome to make Energy Storage more beneficial to power utilities?
- Which technological research needs to be done?
Which energy storage technologies are currently used?

- Lead-Acid, Lithium-Ion, NaS/NaNiCl, VRFB
- Most dynamic Lithium-Ion
- New Candidates: Metal-air, Lithium-Sulfur, Anodes with Silicon, Sodium-Ion (Aquion), Liquid Air, …
- Requirements: safe, cheap, abundant, cyclic and calendaric stability, energy dense, power dense, non toxic
- Candidates fail at least one requirement, usually more
- Time to market min. 5 years rather 10
- Hard to beat Lithium Ion
- However, different applications have different requirements:
  - e.g. UPS matched best by Lead-Acid
  - E2P > 2-4h NaS/NaNiCl + Flow Batteries
Questions / Answers

- What is the status of these technologies? Can they be scaled?
  ≡ In principle …
Scaling up Battery Storage

- Cells cost 1 MWh: 200 T€ - 250 T€
  (Life time today up to 10 years, in 2020 up to 20 years probably realistic)
- Converter cost 1 MW: 100 T€
- System integration 1 MW: 100 T€ (BMS, BOP etc.)

- Cost target
  - 1 MW / 1 MWh ~ 450 €/kW
  - 1 MW / 2 MWh ~ 750 €/kW
  - 1 MW / 3 MWh ~ 1.050 €/kW
  - 1 MW / 4 MWh ~ 1.300 €/kW

- Construction: anywhere within < 6 months
Scaling up Battery Storage

- Modern container vessels carry 15,000 Containers (ca. 400 m x 56 m, 157 kt)
Scaling up Battery Storage

- Modern container vessels carry 15,000 Containers (ca. 400 m x 56 m, 157 kt)
  
  - = 15 GWh (all German PHES together have 40 GWh)
Scaling up Battery Storage

- Modern container vessels carry 15,000 Containers (ca. 400 m x 56 m, 157 kt)

  = 15 GWh / 15 GW (all German PHES together have 40 GWh / 5 GWh)
Questions / Answers

What is the status of these technologies? Can they be scaled?

- In principle …but:
- Safety and standardization: automobile ASIL not applicable
- Prequalification: PCR capacity requirement still uncertain
- Interaction of many inverter connected systems to be investigated
  - i.e. how much synchronous generation is required?
- Regulation/legal: grid connection fees, grid charges applicable?
- Operational experience needed (e.g. proof of durability at real conditions)
- As cell prices drop – other components become more cost critical
Cost reduction strongly dependent on market volume
Electric mobility below 500 €/kWh in 2020
Small stationary systems about 3 x fold cost
Grid connected power in GW

- Freq.Reserve
- Electric cars EV/PHEV
- Domestic PV storage

2023:
- Min: 0
- Max: 15

2033:
- Min: 10
- Max: 70

2050:
- Min: 20
- Max: 180

Perspektive Storage Markets
Germany

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Conclusion

- Electricity storage technologies are available, scaling is technically feasible – the challenge is viability!

- Stationary storage systems at the beginning of commercialization
  - Ancillary Services (PCR, synthetic Inertia, black start, voltage support, …)
  - Domestic PV Storage Systems - plus grid support as secondary use
  - Electric Mobility - during grid connection also grid support

- Major drop in cost of storage (LIB-cells) since 2011 and continue to do so

- Besides research on new chemistries/technologies research on system integration, market introduction and operational experience needed

- Major driver is electric mobility
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