Prospective System analysis of stationary battery systems under the frame of Constructive Technology Assessment

Manuel Baumann

Supervisors:
Dr.-Ing. Marcel Weil
Prof. Dr. Antonio Moniz
Introduction

- German Energy transition
- 80%-100% renewables until 2050
- Mainly based on wind & solar
- Low correlation between RES to load
- Balancing technologies required
- Battery systems are one potential option
- High competition → several technologies

Problem:
- Storage in general depends on other system developments and does not represent a separately identifiable dominant system (Grünewald 2012)
- High uncertainty about general needs and requirements regarding energy storage and sustainability within a large socio-technical regime change → Energiewende

http://www.apricum-group.com
Research Question & Peer Group

- **Research aim:**

  Carry out prospective system analysis based on CTA principles to open technology design processes to related societal requirements & concerns to bring about sustainable improvements of emerging grid battery storage technologies to provide a broader basis for decision making and technology support.

- **Peer Group:**

  Broad spectrum: Technology developers, decision makers & research in the field of stationary battery storage and the energy system
Theoretical background:
Constructive Technology Assessment

- CTA → grounded it theory of **co-evolution** of technology and society, emerging irreversibilities + endogenous futures (Grunwald 1999)

- CTA → several methods → **broaden design process** of new technology **identify undesired impacts** → or make it more **reflexive** (Shot & Rip, 1997)

- If necessary, → **modification** of it → e.g. more **sustainable design** → better fit the **needs of society** (Guston and Sarewitz 2002)

- CTA kernel → **stakeholder participation activities** → surveys, interviews, interactive workshops etc. → increase **social learning**

Source: busyteacher.org
Research Methodology

Problem Definition & Research design

- Literature review & interviews
- Database development

System analysis

- Economic Aspects
- Life Cycle Assessment
- Societal Impacts
- Technology Aspects

Multi-Criteria-Decision-Analysis

AHP + TOPSIS

Decision Making & Technology Development Support
Explorative research for Stakeholder involvement

Supervised master thesis of Thom Versteeg → exploratory work about CTA to battery storage (qualitative, interviews & survey)

- 8 interviews, 220 invitations → 33 responses
Stakeholder involvement: Survey

- Online Survey
- 2 Languages, spreaded globally
- Stakeholders within dominant socio-technical system (energy system)

Welcome to the survey on stationary battery systems

Dear participant,

thank you for your interest and participation in this research on energy storage technologies. The following survey takes about 15 minutes and is completely anonymous. The results will only be used in line of this research. You can also receive a summary of the results if requested.
## Stakeholder involvement: Starting point/stakeholder identification

- Dominant socio-technical regime concept - 7 sub regimes and corresponding stakeholder groups in energy storage + exploratory work Thom (Geels & Verbong 2010 & Grünewald 2012, Versteeg 2014)

<table>
<thead>
<tr>
<th>ST-regime dimension</th>
<th>Stakeholder group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry</td>
<td>Utility companies, networks operators, developers</td>
</tr>
<tr>
<td>Technology</td>
<td>Developers, Academia</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Transmission &amp; Distribution System operators (TSO &amp; DSO), utilities, academia</td>
</tr>
<tr>
<td>Policy</td>
<td>Policy makers, regulators, academia</td>
</tr>
<tr>
<td>Culture</td>
<td>Society</td>
</tr>
<tr>
<td>Science</td>
<td>Academia, Industry</td>
</tr>
<tr>
<td>Market User preferences</td>
<td>Utilities, TSO´s, DSO´s, demand Aggregators, End users,</td>
</tr>
</tbody>
</table>

Based on Grünewald et. Al 2012
Survey: Methodological procedure

- **1st Pretest phase:** In ITAS (about 10 persons performed technical tests, individual, informal discussion with 5 participants), presentation of criteria & stakeholder groups in the working group + short feedback

- **2nd Pretest phase:** consultation of **11 external experts** → research and industry, → to make a **critical review** and to participate in interview → **8 pre-test interviews*** → identify problems regarding questions, relevance of stakeholders & used criteria for MCDA Methods

- **3rd Pretest phase,** technical pretest (working group → 5 tests)

- Release of survey

- Follow-up interviews

*Source: prosoft-technology.com

*cognitive interviews : probing (comprehension, category selection,) (Schuman 1966 & Belson 1981) / Semi structured 30 to 120 minutes per telephone & personal
Survey
Structure after pretest phases

The survey is structured in 3 „parts“

1. General questions regarding the „Energiewende“
   - Potential impact of RES on markets & system safety
   - Structure of the future energy system (central vs. decentral)
   - Relevance of different balancing technologies
   - ....

2. Stationary battery related questions
   - Level of system integration
   - Application fields
   - ...

3. Multi-criteria decision analysis (MCDA)
   - Identification of sustainability hotspots regarding balancing technologies through MCDA
Survey: Participants of the survey

- After external reviews 13 Stakeholder groups

- A relevance list of SH was developed, (internet research, personal contact, business contacts)

- > 80 individual invitations …3 days of email writing

- PIs, higher management, project leaders

- Snow-ball principle

- Target: 6 participants per stakeholder group

Source: hardwaresecrets.com
Survey results:
Participants of the survey
Survey: Participants

Since 27.10.2015 - > 50 responses (> 40 completed entire survey, including usable external pretests) – survey deadline 30th of November

Total participants

- Utility company: 10
- Network operator: 3
- Municipal utility: 4
- Renewable energy production/retail: 4
- Energy storage Business (planning etc.): 6
- Battery research & development (University, research center etc.): 6
- Research - Energy system (University, research center etc.): 10
- Regulation: 13
- Non-governmental organization (NGO), association: 6
- Battery manufacturer: 3
- Automotive sector (electric mobility, mobility services): 2
- Public body & policy making: 1
- Other: 1

*Other: consulting companies
Survey results:
1. General part (excerpt) I

- Stakeholders were asked to rate the importance of different given technologies for a successful „Energiewende“

  - Demand Side Response
  - Centralized energy storage (pumped hydro, CAES etc.)
  - Flexible power plants (e.g. conventional combined cycle gas turbine)
  - Grid extension measures
  - Modular technologies (e.g. batteries usable in de- and centralized applications)
  - Other relevant technologies

- Other named technologies are: V2G (3 times), P2G, P2H etc.
- Other measures: regulation of RES, tariff systems etc.
Survey results:
1. General part (excerpt) II

- Importance of batteries for RES-based system

[Bar chart showing perceived importance of different technologies]
Survey results:
1. General part (excerpt) IV

Interviews → understand what are the concerns of stakeholders regarding different technologies → Focus batteries

DSM:

„I don´t see a high potential in this technology, ..... smart meters are to expensive, no valuable business case…… acceptance problem also in industry“

Centralized storage:

„Difficult…, really very difficult to implement new projects due to high environmental standards…… and public opinion against new projects…. No real alternative… markets are not sufficient“

Grid extension:

„Well very necessary… but I think we all know the problems…. NIMBY…“

Battery storage:

„We are already at the minimum edge of profitability with pumped hydro – how should new concepts as batteries then be economically viable?“
Survey results:
2. Battery specific part (excerpt)

- Visions from SH → stationary battery systems application & system integration in the future

Where will system integration take part? What kind of application is probable?
Assumption → way of designing & selecting technology according to sustainability factors relies on the preferences from different actors embedded in different “worlds” (sub-regimes) → complex decision problem → temporarily dominant ST-regime

Dilemma uncertainty of the desirable technology “shape target” → weighting of results → environmental vs. economic vs. social aspects → what is relevant → factors to improve embedding in society

MCDA serves as integral part to link qualitative and quantitave results
MCDA - AHP: Multi-Criteria-Decision-Analysis (MCDA)

What is MCDA?
- Conjunction of mathematical procedures to systematically visualize the optimum choice of alternatives for a decision maker

Why use it?
- Complexity of decisions due to
  - Multiple objectives (min cost, max benefit)
  - Complex structure (several alternatives, views etc.)
  - Sequence of decisions (decision dependent on former decisions)
  - Multiple decision makers (various views, objectives etc.)
- Often appear in combination with high uncertainty
MCDA - AHP: MCDA – Model

- Several methods available (ELECTRE, SMART, ORESTE etc.)
- Which one is suitable for my approach?

Analytic Hierarchy process AHP

- AHP method based on mathematics and principles of psychology
- Allows to obtain physical factors + allows to access psychological realm
- Non-linear framework, considers several factors simultaneously, allows for tradeoffs to arrive at a synthesis (Saaty 1990).

MCDA - AHP: MCDA – Model

AHP

Qualitative data

State problem

Determine Alternatives

Identify criteria

Structure Hierarchy

Pair wise comparison

Calculations

CR > 0.1

Yes proceed

Overall weights / priorities

Technology Ranking; Relevant factors for technology choice

TOPSIS

Quantitative system analysis: (LCA, LCC, etc.)

Normalized decision matrix

Construct weighted normalized matrix

Determine ideal and negative ideal solution

Calculate separation measurement (euclidean distance)

Calculate closeness to ideal solution

*Technique for Order Preference by Similarity to Ideal Solution
MCDA - AHP: Definition of Alternatives

- Battery technologies → based on survey & interviews
  - Redox-flow-Vanadium-battery
  - Lithium-Iron-Phosphate-Battery
  - Lead-acid (VRLA)
  - High-temperature-battery (Zebra)

- Alternative technologies for comparison
  - Pumped Hydro Storage
  - Combined cycle gas turbine
  - Not possible to include all flexibility options
MCDA - AHP: Definition of Criteria

- Start with a comprehensive literature review to get overview
  - 4 main criteria
  - 11 sub-criteria

- First set of criteria – was then discussed internal & reformulated

- Presented to pre-testing SH group

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Criteria</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources</td>
<td>[106], [42], [116], [117], [103]</td>
<td>3</td>
</tr>
<tr>
<td>GHG emissions</td>
<td>[106], [116], [42], [119], [120]</td>
<td>5</td>
</tr>
<tr>
<td>Impact on ecosystems</td>
<td>[42], [117]</td>
<td>2</td>
</tr>
<tr>
<td>Risk in cause of failure</td>
<td>[117]</td>
<td>1</td>
</tr>
<tr>
<td>CO2 Emission</td>
<td>[42], [121], [109]</td>
<td>3</td>
</tr>
<tr>
<td>CED</td>
<td>[109], [122]</td>
<td>2</td>
</tr>
<tr>
<td>Land use</td>
<td>[109], [121], [119], [119], [120], [115]</td>
<td>1</td>
</tr>
<tr>
<td>SO2</td>
<td>[109]</td>
<td>1</td>
</tr>
<tr>
<td>NOx</td>
<td>[109], [122]</td>
<td>2</td>
</tr>
<tr>
<td>Particles</td>
<td>[122]</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>[119], [120], [119]</td>
<td>3</td>
</tr>
<tr>
<td>Specific cost, LCOE, LCC</td>
<td>[121], [117], [118], [118], [122], [129], [115]</td>
<td>7</td>
</tr>
<tr>
<td>Enth. Of comp.</td>
<td>[117]</td>
<td>1</td>
</tr>
<tr>
<td>Investment Cost</td>
<td>[42], [121], [109], [122], [119]</td>
<td>5</td>
</tr>
<tr>
<td>O &amp; M Cost</td>
<td>[42]</td>
<td>1</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>[119]</td>
<td>1</td>
</tr>
<tr>
<td>Payback method</td>
<td>[42], [123], [119]</td>
<td>3</td>
</tr>
<tr>
<td>NPV</td>
<td>[119]</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>[117], [118], [122], [42], [119]</td>
<td>5</td>
</tr>
<tr>
<td>Compliance with pol goals</td>
<td>[108], [117]</td>
<td>2</td>
</tr>
<tr>
<td>Nat. indep.</td>
<td>[117]</td>
<td>1</td>
</tr>
<tr>
<td>Employm. Pot., new jobs</td>
<td>[117], [109], [123], [119], [120], [115]</td>
<td>5</td>
</tr>
<tr>
<td>Social accept.</td>
<td>[42], [108], [117], [119], [115]</td>
<td>5</td>
</tr>
<tr>
<td>Effects on landscape</td>
<td>[117], [118]</td>
<td>2</td>
</tr>
<tr>
<td>Social Benefits</td>
<td>[42], [115]</td>
<td>2</td>
</tr>
<tr>
<td>Risk</td>
<td>[118], [115]</td>
<td>2</td>
</tr>
<tr>
<td>Contribution to regional dev.</td>
<td>[123]</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>[118], [122]</td>
<td>2</td>
</tr>
<tr>
<td>Efficiency</td>
<td>[117], [116], [117], [122], [123], [119]</td>
<td>5</td>
</tr>
<tr>
<td>Exergy efficiency</td>
<td>[116]</td>
<td>1</td>
</tr>
<tr>
<td>PER</td>
<td>[115]</td>
<td>1</td>
</tr>
<tr>
<td>Safety</td>
<td>[119]</td>
<td>1</td>
</tr>
<tr>
<td>Reliability</td>
<td>[42], [118], [119]</td>
<td>3</td>
</tr>
<tr>
<td>Maturity</td>
<td>[42], [116], [118], [123]</td>
<td>4</td>
</tr>
<tr>
<td>System life</td>
<td>[119]</td>
<td>1</td>
</tr>
<tr>
<td>Availability</td>
<td>[119]</td>
<td>1</td>
</tr>
<tr>
<td>Fatals</td>
<td>[120]</td>
<td>1</td>
</tr>
<tr>
<td>Flexibility</td>
<td>[115]</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>[117], [118], [120], [115]</td>
<td>4</td>
</tr>
</tbody>
</table>
MCDA – AHP: Final set of criteria

- **Interviews** and **external reviews** have led to stepwise alterations and changes → final set of criteria.

![Diagram of Technology evaluation and choice with sub-criteria and main criteria]

**Objective**

**Main Criteria**

- **Ecology**
- **Economy**
- **Technology Aspects**
- **Society & Policy**

**Sub-Criteria**

- Eco-system
- Human health
- Ress. availab.
- Invest. Cost
- Life Cycle Costs
- Maturity
- Techn. Perf.
- Techn. Flexibilit y
- Socio econ.
- Accept.

**Sub-Criteria II**

- Technical aspects
- Socio-economical aspects
- Environmental aspects
- Legal aspects
- Technical aspects

**Technology option X, Y, Z......**

Comparison 1

Comparison 2-5

Quantification, TOPSIS
MCDA - AHP: Pairwise Comparisons

1. Please state your preferences regarding sustainability aspects of storage or balancing technologies (e.g. battery storage, gas turbines, pumped hydro storage, etc). Rate the following aspects by pairwise comparisons for the AHP evaluation. The categories represent the three pillars of sustainability and are supplemented with a fourth category “technology”.

Sustainability criteria overview:
- **Ecology** = Subcriteria: Damage to ecosystem diversity, damage to human health and resource availability
- **Economy** = Subcriteria: Capital cost and lifecycle costs
- **Society & Policy** = Subcriteria: Social acceptance, availability of regulations, compliance with political goals
- **Technology** = Subcriteria: Technological maturity, performance and flexibility

![Pairwise Comparison Diagram]

- Ecology
- Economy
- Society & Policy
- Technology

---

25 11.12.2015 Manuel Baumann
MCDA - AHP: Pairwise Comparisons

1. Please state your preferences regarding sustainability aspects of storage or balancing technologies (e.g. battery storage, gas turbines, pumped hydro storage, etc). Rate the following aspects by **pairwise comparisons** for the AHP evaluation. The categories represent the three pillars of sustainability and are supplemented with a fourth category “technology”.

Sustainability criteria overview:

**Ecology** = Subcriteria: Damage to ecosystem diversity, damage to human health and resource availability

**Economy** = Subcriteria: Capital cost and lifecycle costs

**Society & Policy** = Subcriteria: Social acceptance, availability of regulations, compliance with political goals

**Technology** = Subcriteria: Technological maturity, performance and flexibility

![Pairwise Comparisons Diagram]
MCDA - AHP: Pairwise Comparisons

- Results from the survey
- Transformation in suitable scale
- For each stakeholder
MCDA - AHP: The math....

RESULTS
Example of preferences of 2 stakeholders that participated
MCDA – AHP: Group decision making

- Creation of BCG like matrice for main criteria

13 Utility Comp.
12 Netw. Operator
11 Municipal Utility
10 RES Integr.
9 EES Business
8 Battery Res.
7 Research Energy
6 Regulation
5 Civil Society
4 Battery Manuf.
3 Automotive Ind.
2 Public Body
1 Other
MCDA – AHP: Group decision making

- Aim of this AHP is to come to **group decisions** to
  - select key performance parameters
  - To agree on common strategies for future developments
  - How to derive → average → unclear if stakeholder agree with each other
MCDA – AHP: Consensus factor

- Concept of diversity → shannon entropy* S (Shannon** 1948)

- S + alpha & gamma diversity → biology (Jost, 2006).

- Result is a homogeneity index → consensus indicator

- Consensus will be 0 when priorities are completely distinct and 1 when they are identical (Goepel 2013)

  - 0 % no consensus → 75% high consensus → 100 % absolute consensus

  - This can be used to analyze how strong consensus is among stakeholder groups

* to measure of unpredictability of information content  **Inventor of the bit
MCDA-AHP: Results per group

- 4 field matrices to identify main criteria relevant for technical choice/design

Acceptable value of consistency > 75%
Groups agree to a high degree within them selves; minimum consistency is 20% due to graphical reasons
MCDA-AHP: Detailed Stakeholder analysis

- Gather deeper insight in Stakeholder decisions
- Shared Interest → pairwise kxk-Matrice → spot pot. „alliances“

Further discussion → develop new alternatives for given problem
MCDA-AHP: Detailed Stakeholder analysis

- For all Stakeholders, multiple interest clusters k=62, common priorities

Interest clusters

Degree of consensus

- Absolute
- Very Strong
- Strong
- Good
- Moderate
- Low
- Very Low
- None

Analysis pending…
MCDA-AHP: Detailed Stakeholder analysis

- Relation of priorities in technology design/Invest decision

Consensus: 0

Consensus: 80%

- Environment
- Economics
- Technology
- Social Aspects

1 Utility

42 Municipal Utility

53 RES R&I
MCDA-AHP
Sub-criteria

- Vector summation for sub-criteria weights for all SH → consensus relatively high

Life cycle view has highest priority

High relevance of maturity and performance

Social Acceptance perceived most critical

Clear priority of human health
MCDA-AHP
Combination of models

Qualitative data:
Stakeholder weights

Quantitative system analysis:
(LCA, LCC, etc.)

AHP

TOPSIS

Technology Ranking; Relevant factors for technology choice
MCDA-AHP: Results

- Comparison of technologies based on mcda and stakeholder groups
- Obtain average optimum of technology (LCA results not real)
MCDA-AHP: Results

- Ranking of Storage technologies base on obtained sustainability criteria and weights
- Enables in depth analysis of criteria contribution to final result

![Bar chart showing total scores for different storage technologies: LFP (0.43), NaNiCl (0.42), RFB (0.41), GasTurbin (0.32), PHS (0.31), Blei (0.31).](chart.png)
Conclusion & Outlook

- AHP → multiple constructed realities in differences within perceptions, attitudes, judgements and practices of various actors and makes them transparent and debatable.

- Solid base for SH modulation following the principles of CTA by allowing differences in opinions to develop a best construct of technology

- Integrative approach → combine CTA & quantitative system analysis tools to explore potential sustainability implications
Outlook

- Interpretation of survey results
- Quantification of results (LCA under construction)
- Continue writing