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Battery storage systems as balancing option in intermittent renewable energy systems - A transdisciplinary approach under the frame of Constructive Technology Assessment

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“Do dito ao feito, há muita distância.” - unknown

“*tlhutlhmeH HIq ngeb qaq law' bIQ qaq puS”* - famous klingon saying

Manuel Baumann

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Resumo

Face ao aumento da descentralização da rede de energia, as diferentes opções tecnológicas de armazenamento em bateria, são consideradas como uma importante opção flexível.

O desafio está em apoiar o processo de tomada de decisão, fornecendo uma perspetiva mais ampla sobre o desenvolvimento tecnológico em baterias, a sua escolha e implementação.

Uma abordagem personalizada, à luz da avaliação de tecnologia construtiva, em combinação com a análise do sistema, permite explorar eficientemente as visões e expectativas dos atores sobre o armazenamento de energia em baterias, para fornecer informação (qualitativa e quantitativa) sobre as suas consequências. Deste modo, as visões e expectativas de atores relacionados com o desenvolvimento da tecnologia é confrontada com a dos atores não relacionados com este processo (“enactors” e “selectors”) de modo a criar um novo e vasto conhecimento para fornecer uma tecnologia mais sustentável.

As principais implicações identificadas para o sucesso da bateria mostram falta de modelos de negócios, regulamentos incertos e dúvidas sobre sua viabilidade tecno-económica. A salientar a confirmação de que as expectativas compartilhadas acerca das propriedades da tecnologia, em consonância com sustentabilidade, são resolvidas em perspetivas concêntricas usando o Processo de Hierarquia Analítica (AHP).

Enquanto que os *“enactors”* concentram-se no desempenho económico e tecnológico, o que reflete o viés concêntrico deste grupo, os “*selector*” percecionam os critérios de impacto ambiental e social como mais importantes. O consenso geral entre os atores em relação às diferentes dimensões dos objetivos do desenvolvimento da tecnologia, é baixo a moderado. A análise do sistema é usada para quantificar as preferências dos atores obtidas através do AHP. As baterias de iões de Lítio (LIBs), as baterias de chumbo-ácido (VRLA), as baterias de alta temperatura (NaNiCl e NaS) e as baterias Vanadium-redox-flow (VRFB) foram avaliadas usando por exemplo a avaliação do ciclo de vida e os custos em quatro campos de aplicação (armazenamento descentralizado, suporte de energia eólica, regulação primária e deslocamento de tempo de energia (ETS-inclui armazenamento de energia de ar comprimido (CAES) e armazenamento de bombeamento-hídrico (PHS)).

Os rankings preliminares indicam que a maioria das LIBs podem ser recomendadas para todas as áreas de aplicação identificadas. VRLA e NaS foram classificadas em último lugar, enquanto o ranking da VRFB é altamente dependente do uso considerado. PHS e CAES dominam todas as tecnologias de bateria avaliadas no caso das ETS.

Palavras chave: Armazenamento de energia da bateria, avaliação construtiva da tecnologia, sistemas de energia renovável, tomada de decisão, LCC, LCA, MCDA

Abstract

Different battery storage technologies are considered as important flexibility option in the face of increasing shares of renewables in the grid. A challenge is to support decision-making by providing a broader perspective on battery technology development, choice, and implementation. The tailored approach in the frame of Constructive Technology Assessment (CTA) in combination with system analysis allows it to explore actor visions and expectations about battery storage and to use this information to provide quantitative information about the consequences of these.

Research results combine the perspectives of technology and non-technology related actors (enactors and selectors) to create new and broader knowledge to provide “better” technology. Major implications identified for battery storage are missing business models, uncertain regulations, and doubts about their techno-economic viability. A highlight is a proof that expectations about technology characteristics in orientation to sustainability criteria are settled within concentric perspectives by using the Analytic-Hierarchy-Process (AHP). Enactors focus on economic and technological criteria which reflect the concentric bias of this group. In contrast, selectors perceive environmental and social criteria as more important. The consensus among actors regarding criteria importance is not existent to moderate which indicates that more research is required here.

System analysis is used to quantify actor preferences obtained through the AHP. Li-Ion-batteries (LIB), lead-acid-batteries (VRLA), high-temperature-batteries (NaNiCl and NaS), and Vanadium-redox-flow-batteries (VRFB) are evaluated through e.g. life cycle assessment and costing for four different application fields (decentralized storage, wind energy support, primary regulation and energy-time-shift (ETS-includes compressed-air-energy-storage (CAES) and pumped-hydro-storage (PHS)). Preliminary rankings indicate that most LIBs can be recommended for all application areas, wherein decentralized storage is considered to offer the highest potentials for battery storage. VRLA and NaS achieve rather low scores whereas ranking of VRFB is highly dependent on the considered use case. PHS and CAES dominate all assessed energy storage technologies in the ETS application case.

Keywords: Battery energy storage, renewable energy systems, constructive technology assessment, decision making, MCDA, LCC, LCA

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Abbreviations

AHP	Analytic hierarchy process
CAES	Compressed air energy storage
C-DEEPSO	Canonical particle swarm optimization algorithm
CES	Centralized energy storage
COE	Cost of electricity
CTA	Constructive technology assessment
DSM	Demand side management
ETS	Energy time shift
HMGS	Hybrid microgrid systems
LCA	Life cycle assessment
LCC	Life cycle costing
LFP	Lithium-iron phosphate
LMO	Lithium manganese oxide
LTO	Lithium titanate oxide
LPSP	Loss of power supply probability
MCDA	Multi-criteria-decision-making
MODM	Multi-Objective Decision Making
NaNiCl	High temperature sodium-nickel-chloride
NaS	Sodium sulfur battery
NCA	Nickel-cobalt-aluminum-oxide
NMC	Nickel-cobalt manganese-oxide
PHS	Pumped hydro storage
PR	Primary regulation
RES	Renewable energy sources
SoC	State of charge
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VRFB	Vanadium-redox-flow-battery
VRLA	Valve-regulated lead-acid

1 Introduction

It is common sense that the German “Energiewende” represents a large socio-technical transition of the current energy system towards a more sustainable and renewables based one. The transition process is characterized by increasing fluctuating renewable energy system (RES) capacities leading to a higher demand of flexibility options as energy storage technologies in the mid to long term [1], [2], [3], [4]. Battery storage systems with various existing as well as emerging chemistries and vertical system integration possibilities are such a storage technology in the foci of this research. They are told to represent an enabling technology to achieve a more sustainable electricity system consisting of RES, grid infrastructure, residential power generation, power plants, and regulation. Vice versa they are dependent on other energy system developments as well dynamics and do not represent a separately identifiable dominant system [5]. Their success is dependent on hardly predictable future technical advances, actor preferences, development of competing technologies and designs, diverging interests of actors, future cost efficiencies and environmental performance as well as the evolution of market demand and design. All these dependencies can lead to engineering skepticism regarding technologic and economic viability or public concerns whether high costs of this technology might not outweigh possible benefits [6] within the energy system.

A legitimate question arises here about the expectations and visions of society regarding the characteristics and future role of electrochemical energy technologies. The role of stationary battery storage technologies within the energy system remains blurry in theory and practice. There is a multitude of studies available that aim to access the future role of emerging storage technologies and their impacts as well as benefits. Such attempts are often labeled as sustainability assessments entailing multiple dimensions as environmental impacts or economic performance of energy storage and in some cases, provide a quantification of these. Such multi-dimensional perspectives inhibit conflicting values, different moral positions, and belief systems when it comes to the promotion of such “better” technologies (may it be in environmental, economic or social terms). Such expectations and visions regarding desired technology properties are a result of social construction that engages certain communities (e.g., locals, industry or governments) in a new way [7]. The creation of “better” or sustainable technology should thus be seen as a process of community-based thinking and learning about the need to integrate environmental, economic and social issues in a long-term view.

This complex interaction of actor interests, market development and blurry notions about the economic, environmental and social stamping of battery energy storage make decision making and technology development more difficult [8]. They have inspired the current research leading to the proposition that there is a strong need to prospectively identify, exploit and exhaust possibilities to shape or select the “best” technology alternatives according to sustainability or better said multi-dimensional assessment principles in a participative and action-orientated way [9], [7]. Providing “better” technology means in this context to avoid unintended effects as wrong investments, possible social conflicts, and negative environmental impacts over the entire life time of new technology rather than to tackle them when they become apparent after the technology has already penetrated society [10].

From this results a need of ex-ante assessment strategies which allow the identification and especially prioritization of such important technology properties and provide a broader basis for decision making, early warning, actor modulation and finally technology support as well as selection. A major implication resulting from this task is the necessity to deal with two worlds, the external world of economics, chemistry, markets and the internal world of psychology, values, thought and of course, decision making itself [11]. The view of constructive technology assessment (CTA) using a transdisciplinary methodology is seen as a strategy able to tackle these tasks.

1.1 Research focus

The research focusses on actor expectations and visions on the uptake and desirable properties of stationary electrochemical energy storage systems and compares them with other energy storage options in the context of a changing energy system and different application fields. It furthermore takes a constructive technology assessment (CTA) stance as an ex-ante strategy to open innovation processes, to enable social learning, reflexivity and the development and choice of the “best” or sustainable technology using a set of environmental, economic, technology and social criteria. A transdisciplinary oriented approach is tailored in the frame of CTA in which academic and non-academic stakeholders are actively incorporated into the research. This is realized by a combination of semi-structured interviews, online surveys, system analysis and multi-criteria decision-making methods (MCDA). System analysis methods include life cycle costing, life cycle assessment- and techno-economic characterization of different energy storage technologies to identify conditions that enable a “better” embedment of technology in society. MCDA combines stakeholder expectations from science, industry, academia, and politics as well as system analysis results to unveil the consequences of the actors notions about an optimum construct of battery storage technologies. These expectations are then discussed and analyzed comprehensively through the goggle of CTA.

1.2 Hypothesis and research question

Technology is developed, produced and used by a multitude of organizations with different temporarily valid technological capabilities, interests, and beliefs [6]. The presented research is based on the hypothesis that energy storage technology design and selection according to societal needs form a complex decision problem under high uncertainty underlined by multiple expectations of what the future will look like. A design and decision dilemma arising from the claim to achieve something as “better or more sustainable technology” is to find the right shape target (e.g., environmental vs. economic vs. social aspects) and how to characterize these. This phenomenon is often associated with the so-called Collingridge dilemma [12] which states that: in early technology development stages opportunities to steer are plentiful, but hard to choose from, while at later stages this is reversed [13] [12]. This problem is reinforced by the fact that sustainability is a “wicked problem” meaning that there is no definitive formulation of it. Consequently, there is also no “best” technological solution.

Notions about sustainable or “better” technology properties rely on diverse expectations from different actors embedded in different “worlds” (e.g., organizations) within a temporarily dominant socio-technical regime, in this case, the energy system. The power of these expectations depends on the degree to which they are shared among the system. This degree of ‘sharedness’ ensures that stakeholders act accordingly and rational to these expectations. CTA offers a possibility to tackle this dilemma by broadening the design of new technologies by feedback of technology assessment activities into the construction of technology [14]. By nature CTA has a transdisciplinary research orientation which allows to; 1) incorporate processes, methodologies, knowledge, and goal of stakeholders from and across academia as well as actors from outside academia, 2) to create solution-oriented and social robust knowledge which is transferable to scientific and societal practice [15], [16], [17].

Chapter 2 will unveil gaps within the literature regarding battery energy storage its future use and sustainable stamping in the energy system, while chapter 3 gives a detailed overview of the briefly mentioned grounding concepts of this research which have both led to the following overall research question:

> **What is the future role of different stationary battery storage technologies within the German energy turn-over and what expectations do actors have regarding their characteristics?**

The research targets a broad peer group, starting with technology developers, users, decision makers & research in the field of stationary battery storage and the energy system.

1.3 Objectives of the research

This work follows the ex-ante heuristic of constructive technology assessment (CTA) [18] which serves as a guiding principle [19]. CTA has the aim to broaden the early design process of (electrochemical energy storage) technologies by including more actors and aspects to realize a better technology in society [20]. Critical parameters and conditions over the entire battery life cycle have to be identified to achieve the latter. Life cycle based system analysis methods, more specifically life cycle costing and life cycle assessment are seen as suitable approaches to unveil major sustainability conditions. Participative measures and social learning represent the kernel of CTA as a transdisciplinary research framework and enable it to open up the innovation process of technology. Thus, system analysis as a more quantitative approach is flanked by participative measures as surveys and interviews to; a) gather stakeholder expectations on energy storage and b) identify critical factors and to include their characterization into technology evaluation. Both, quantitative and qualitative methods are merged through a multi-criteria decision analysis to find an “ideal” solution to meet societal demands nowadays. The following objectives have been set to fulfill this:

- Carry out a comprehensive literature review on electrochemical energy storage and implications in general through changing markets, technologies, and electricity system conditions in Germany to identify driving forces for energy storage need and development
- Develop and operationalize an integrative approach using CTA as a research framework
- Identify future socio-technical implications and include non-linearity of technology development paths (applications fields, relevant actors, potential market or drivers) by the involvement of stakeholders
- Identify quantitatively and comparatively actors notions about the relevance of critical parameters over the entire life cycle of selected electrochemical energy storage systems based on life cycle thinking and on a broader sense sustainability

- Analyze these preferences, their sharedness and quantify these via modeling
- Provide a ranking of factors relevant for technology choice by multi-criteria decision analysis methods (Analytic Hierarchy Process) including a indicative ranking of technologies.

1.4 Research structure

The structure of this work is based on nine chapters. Chapter 2 represents a critical literature review on energy system development, energy storage demand, electrochemical energy storage and studies related to battery storage technology choice regarding different sustainability dimensions. In the end, major implications are derived from this review. The third chapter highlights theoretical assumptions for CTA and interrelations to sustainable development. It explains the theoretical groundings of employed threads used in this research to answer the questions raised. Firstly, it starts with the illumination of socio-technical dynamics, emerging irreversibilities and entrenchment and sustainability as an implicit meta-goal for CTA to create “better” technology. Finally, major process steps, assumptions, and goals as well as the transdisciplinary characteristics of CTA are highlighted and discussed briefly.

The research framework is presented in chapter 4. A specification of the research questions is conducted on the base of chapter 2 and 3 by setting up a hypothetical decision process. The used methods as system analysis methods as life cycle assessment and costing (LCA and LCC) are outlined together with the integrative concept of multi-criteria-decision analyses. The chapter is concluded by the presentation of the analytical framework used to tackle identified research questions. Stakeholder expectations on the energy system and battery storage development are unveiled in chapter 5. Interview and survey results are summarized, interpreted and analyzed statistically. First, the role of battery storage among other flexibility options, relevant developments in markets and the relevance of sustainable development for storage technology design and investment are explored. In the second half, specific expectation and visions on battery storage are analyzed. Results are then summarized and used to illuminate potential implications that might have an impact on battery storage development and their market introduction and further steps for modeling.

Chapter 6 is indirectly related to chapter 5 as the MCDA is carried out together with the survey. It introduces MCDA methods, namely the analytic hierarchy process (AHP) which is used to gather actor preferences and to calculate consensus among participants. After that, a description of how different criteria were chosen based on stakeholder references is given. The aggregation of stakeholder preferences and modeling results is realized using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

In chapter 7 the quantification of selected criteria and alternatives through system analyses methods and intermediate results are presented together with a sensitivity analysis. First selected social and technological criteria a described in detail in this chapter. A high emphasis is put on the approaches of LCC and LCA by highlighting major calculation steps and assumptions in combination with corresponding sensitivity analyses. Results are presented in chapter 8 by depicting general priorities, group preferences, consensus, indicative technology rankings and related sensitivities. The conclusion is provided in chapter 9 wherein every stated research question is tackled by an own sub-section. In the end, the entire research is discussed and provides an overview of major findings of this research.

2 Electric energy storage for the power system

The following sections provide a literature review to study recent and future developments of the German power system related renewable energy system (RES) and the potential need, requirements, impacts, and selection of energy storage technologies. This review aims to identify major gaps related to battery energy storage choice and application. The first part provides an overview of the history and future development scenarios of the German power system. In the following section, potential demand for flexibility resulting from high RES shares is analyzed with a focus on electrochemical energy storage technologies. A summary of the different requirements on energy storage as well as evaluation criteria for technology evaluation is given, which is then contrasted with results from selected multi-criteria decision-making studies. Finally, implications for further research are derived and summarized.

2.1 Historical development of the power system

In the early 50ies, energy consumption in Europe was steadily growing leading to a high rate of large generation capacities owned by a few utilities. These developments were often reinforced through national laws as, e.g., in Germany through the “Energiewirtschaftsgesetz” (EnWG) leading to the formation (and maybe faveolization) of large, centralized and vertical integrated public owned utility companies with defined supply areas. This structures remained in many countries until the 90ies with a national regulation aiming to maintain this structures [21] [5].

Liberalization became a global phenomenon in the early 90ies. Some countries started early with experimenting with liberalized markets like the United Kingdom in 1989, Chile in 1982 or Argentina in 1992, representing pioneers in electricity market liberalization [22]. The reasons for liberalization are different for each country but mainly have the objective to reduce end-user energy costs in relation to monopolized markets, to reduce external especially political involvement including regulatory measures as well as to open markets for new entrants. Additional drivers for liberalization were political ideology on the faith of market forces, the desire to attract foreign investment, distaste for strong unions and environmental concerns [22].

Liberalization of energy markets in Europe started in the late 90ies and is based on the three-pillar policy of the EU namely energy security, competitive markets and the development of renewable energy sources [23] and includes further strategic and political goals (directive 2003/54/EG) [22]. The directive has led to a severe transformation of the former state-owned highly vertical integrated energy companies in Germany. The companies were obliged to conduct an ownership and legal unbundling of their divisions of electricity generation, transmission and distribution (grid) as well as consumption.

Parallel to liberalization a strong promotion of renewable energy systems as photovoltaics and wind turbines, e.g., through EU directives 2001/77/EC took place which has set challenging indicative national targets to increase RES shares [23]. Several promotion strategies were adopted simultaneously to liberalization in Europe in the form of investment focused (investment incentives, tendering systems, environmental taxes, etc.), generation based (Feed-in tariffs, tendering system for long term contracts, etc.) and voluntary focused measures (Investment focused shareholder programs, voluntary agreements) [23]. This action has led to a massive growth of RES in several countries as Germany, Spain, and others since the year 2000. The establishment of the European Emission Trading System EU- ETS 2003/87/EG and the definition of the EU 2020 targets[1] in the frame of the Kyoto goals are also seen as an important factor for this development [24].

German utilities have become more short-term and cost competition oriented due to the liberalization of the sector. They maintained a conservative investment behavior and invested heavily in the conventional generation before the renewables rush began [25]. This has led to a long delay of investment through electricity utilities in the field of RES. Additionally, utilities had to face increasing public pressure to "green" electricity production. This pressure was based on concerns over the impact of climate change, resource depletion and supply security (Russia and the Middle East) and created uncertainty over the long term feasibility of our current system of energy supply [26]. So as RES-technology became more commercially viable, renewables such as wind turbines gained popularity among utility companies, which started to a certain degree to integrate them into the existing power grid. This was also pushed by ambitious German Federal government´s aims to transform German energy supply by cutting down CO_2 emissions by 80% to 95% from the 1990 level until 2050 [27].

An event that has triggered the RES development or even led to a shift in energy system development in at least some countries as Germany was the meltdown of the Fukushima reactors in 2011 through the catastrophic earthquake and the following Tsunami in Japan. This incident has led to the radical decision of politics to force a fast phase-out of German nuclear power plants until the year 2022 [1]. It has furthermore triggered Germany's Energiewende, which has hammered the country's utilities [25]. The resulting overcapacity of conventional power plants built up before the RES rush has caused wholesale electricity prices to tumble. Some conventional power plants cannot make enough money to cover fuel costs and are being shut down. The Fukushima incident represents a different and unforeseeable landscape change that increased regime problems that have led actors, mainly utilities, to lose faith in regulation, markets, and policy [28]. A good example is the German utility company E.ON which wants to quit conventional energy to focus entirely on renewables [29].

2.2 The future electric energy system

Germany has ambitious targets to produce 35 % of the needed electricity from renewable energy systems by 2020 and over 80 % by 2050 within the so-called "Energiewende" - Energy transition [30] which is flanked by the German federal government. The energy system is complex, and a high magnitude of uncertainties characterizes future developments to achieve these goals. This has motivated the creation of numerous variations of energy system development scenarios as [31], [27], [32], [33]. One of the most cited scenarios for RES shares within the German Energiewende is based on DLR [27]. The scenarios have been built in orientation to the goals of the German federal government and illustrate the associated structural changes over time. They also highlight different paths of the developments in the transport sector which is closely linked to the power industry. An overview of all considered scenarios with a detailed insight is given in Figure 2-1. In total three main scenarios 2011

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[1] The targets are to cut greenhouse gas emissions by 20 %, increase the share of energy from renewable sources by 20 %, increase energy efficiency by 20 % until 2020.

A[2]; B[3] and C[4] were taken into account. These main scenarios were supplemented by two additional scenarios 2011 A[5] and scenario 2011 THG95[6] [27]. The main differences between main scenarios are variations in assumptions regarding the transport sector (use of H_2 and or CH_4). Each scenario results in a share of RES at a gross consumption of around 85 % in 2050. Scenario 2011 THG95 represents the most ambitious variation in which almost the entire energy supply (95%) is based on RES and surpasses the base scenario A, B, and C with about 28 %. Photovoltaics (PV) and On- and Offshore Windpower contribute of 50% to 75 % to total RES generation [34] in all scenarios (bandwidth of min and max penetration scenarios is given in orange in Figure 2-1). The share of low carbon technologies in the electricity mix is estimated to increase from around 45% nowadays and nearly 100% in 2050 [35]. In contrary, conventional generation capacities including coal, nuclear and gas power plants will be drastically reduced from around 85% down to 10 % in 2050.

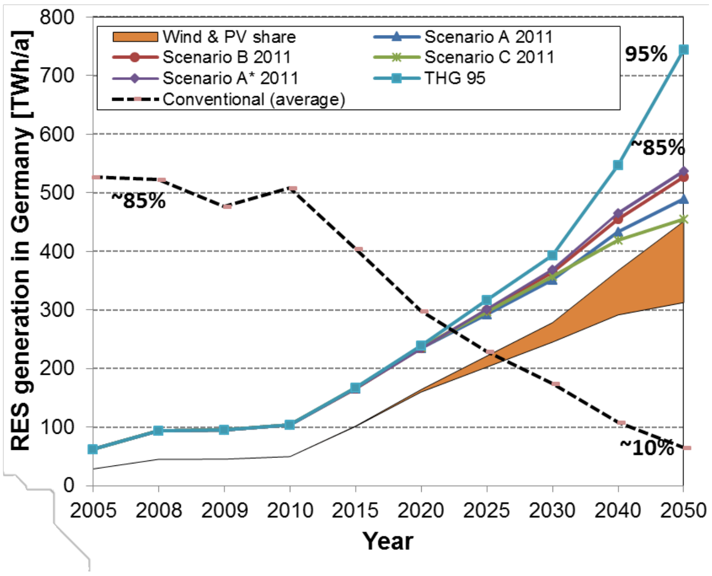

Figure 2-1: Potential RES generation for various scenarios until 2050 (own figure; database [27])

The increasing market roll out of fluctuating decentralized energy resources represents a difficult issue for grid stability. This issue is reinforced by the decreasing number of existing residual energy generation capacity as coal and nuclear power plants. The future grid will have to face greater challenges by providing clean power from a high share of renewables. This increasing share is accompanied with more dynamic loads, less controllable generation capacities [37], excess generation, as well as power flows that occur from low voltage levels from residual energy generation to high voltage grid levels. At the same time, wholesale electricity markets face stronger spot market price deviations.

All these developments are told to lead to a more decentralized structure of generation and foster the development of new structures of the electricity grid known as “smart grids.” Traditional grids have comparatively few point of electricity generation in combination [38] with energy users that are not active

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[2] Base scenario with a middle path of RES growth, including 50% of hybrid passenger cars in 2050 and other forms of alternative transportation technologies. Hydrogen is considered as storage medium for RES – nuclear phase out is considered

[3] Same assumptions as A. It is considered that hydrogen is converted in synthetic methane that is also used in transport

[4] All passenger cars are based on electricity. Consumption patterns are identical to the other scenarios. Hydrogen is only required for long term storage

[5] Includes a reduction of total final energy consumption of 15% by 2050. Assumptions remain the same as in scenario 2011 A

[6] The scenario provides a preview of RES expansion and improvement in efficiency to reach the upper goals of 95% until 2050

participants but just consume the energy supplied by a utility company and pay the energy bill [39]. In contrary, the smart grid represents a highly decentralized system where consumers and generators are connected through advanced information and communication technologies (ICT). More importantly is that users not only consume energy but also produce and supply energy back to the grid. This new type of energy-user is called a “prosumer [39]. The development of smart grids thus represents something striking and new that changes entirely the distribution of roles inherent in energy systems nowadays [40]. An overview of the transition of the classic energy system towards these new systems is given in Figure 2-2.

It can be observed how in the past the energy system was shaped by a one-directional flow of energy where no connection was immanent to users who were merely passive consumers. Conditions in the present changed toward a more integrated system on a transmission grid level where the increasing amounts of ICT. This phase is also strongly shaped by an increasing number of RES. The future phase will be characterized by a highly integrated bi-directional flow of information, money, and energy between customers (encircled in red) and the remaining energy system which itself becomes more complex through the inclusion of new technologies as storage or electric vehicles.

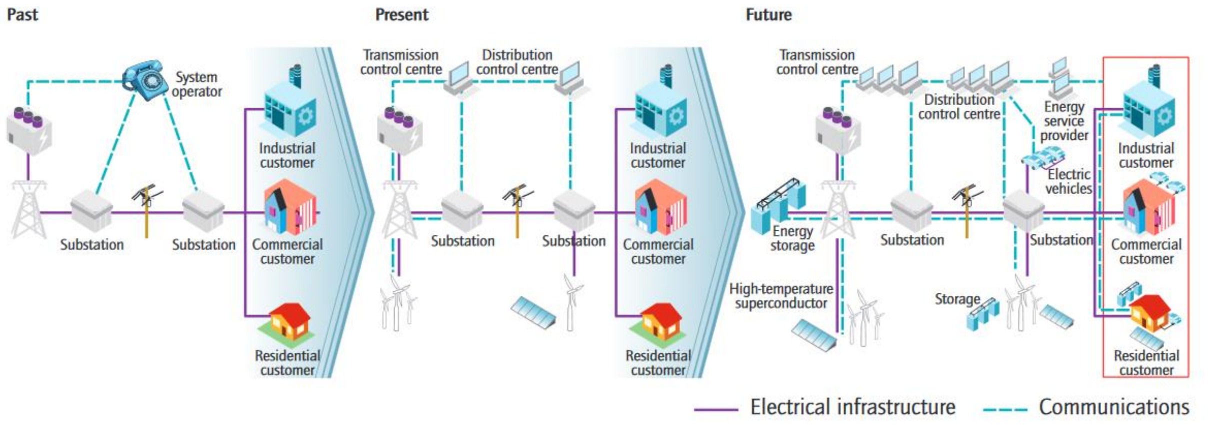

Figure 2-2: Transition of the energy system towards a smarter and interconnected electricity system (source: [40])

2.3 Future need for flexibilization options for RES

The energy system represents to a certain degree an unstable and highly dynamic system due to the stochastic behavior of users or intermittent generators as wind or photovoltaics which have to be continuously coordinated. The reason for this is that single or a collective of users, and the feed-in behavior of such generation units can only be forecasted to a limited degree. Imbalances have thus to be mitigated by continuous and fast adjustment of controllable generation or load units on different time scales. Such balancing services are “up-regulation” that provides additional power in case of high demand whereas “down-regulation” reduces power generation in the system in case of oversupply. Typical balancing technologies are combined cycle gas turbines (CCGT) (only up-regulation) or pumped hydro energy storage (up and down regulation) with high adjustment rates able to provide balancing services [41]. Both regulation forms can also be provided by increasing or decreasing loads. A precondition for balancing it the availability of sufficient electricity transport abilities through electric power networks and sufficient system operation rules to spatially match generation and load. Flexibility is thus an inherent feature of power system design and operation. Intermittent energy sources have a highly fluctuating generation behavior which only correlates partially with load and might occur on a regional level. From this results an increasing demand to balance electrical energy and power to mitigate extreme ramps[7] or excess energy[8]. The degree of flexibility is the ability of a power system to maintain safe operating conditions in the face of growing balancing demand and consequently determines the degree of RES that can be integrated into it [42]. Figure 2-3 provides a simplified schematic of power system operation principles related to flexibility.

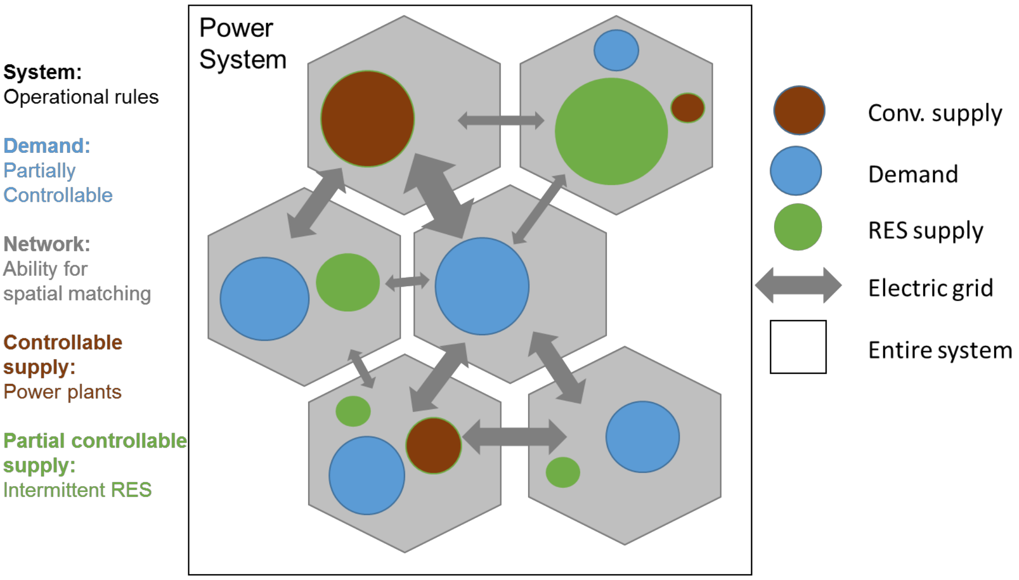

Figure 2-3: Simplified scheme of the electric power system operation principle (adapted from [42])

Fluctuations of a high amount of RES including extreme ramps, excess energy, and forecast errors can cause system blackouts when there is no sufficient balancing option available. The absence of sufficient balancing capacity results in significant challenges for grid operators which have to compensate the variability of an increasing share of decentralized solar and (centralized) wind power to maintain grid stability in the future [37]. A successful integration of renewable energy sources has thus to be realized on different time dimensions of balancing covering seconds, hours to days (e.g. seasonal storage or balancing forecast errors) as depicted in Figure 2-4. The need of flexibility options as energy storage is often intuitively connected to excess energy of RES as the technology is considered as an enabling technology for RES by storing excess energy and feeding it back into the grid in peak times (see pumped hydro storage - PHS charging and discharging in Figure 2-4).

A set of RES studies is compared as depicted in Figure 2-5 to explore potential RES excess impact scenarios for the German energy system until 2050. Each mark represents a single scenario for a specific year. All these scenarios do not have the aim of predicting the future; they rather create a context in which potential development paths can be visualized and discussed [5]. Most importantly they allow it to identify to a certain degree potential consequences of different transitions paths of the energy system or energy storage respectively.

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[7] Extreme changes of a generation units power output within seconds to minutes

[8] Amount of generated electricity that surpasses demand in combination with must run power plants

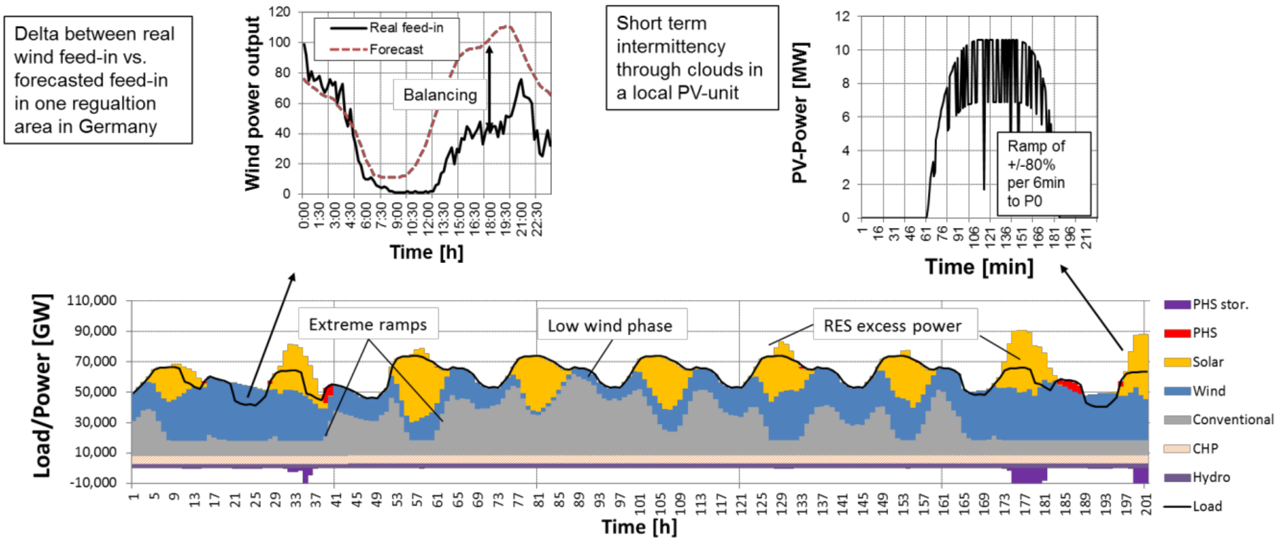

Figure 2-4: Illustration of extreme RES impact on the German energy system in 2025 (simulated on base of [43])

It can be observed in Figure 2-5 that most scenarios draw a pretty common picture until the year 2035. Starting from this point results become more diversified due to a high amount of uncertainties and influence parameters in 2050 (variations of excess energy from 0 TWh up to 100 TWh and a median of 23 TWh). Genoese [2], DB research 2013 [44] and Fraunhofer ESP 2011 [45] tend to have relatively moderate and comparable impact scenarios while SRU 2011 [33], Ökoinstitut 2014 [46] and UBA 100% [47] are considered with higher RES impacts of up to 100 TWh per year. Nevertheless, a take-off of RES-excess energy production is considered to start at a share of 60% in most cases (see red line that indicates a 2nd-degree polynomial regression of indicated median values in Figure 2-5). The assumptions about the amount excess energy through RES often serve as a base for simulations to identify the potential need for balancing options which will be presented in the next chapter.

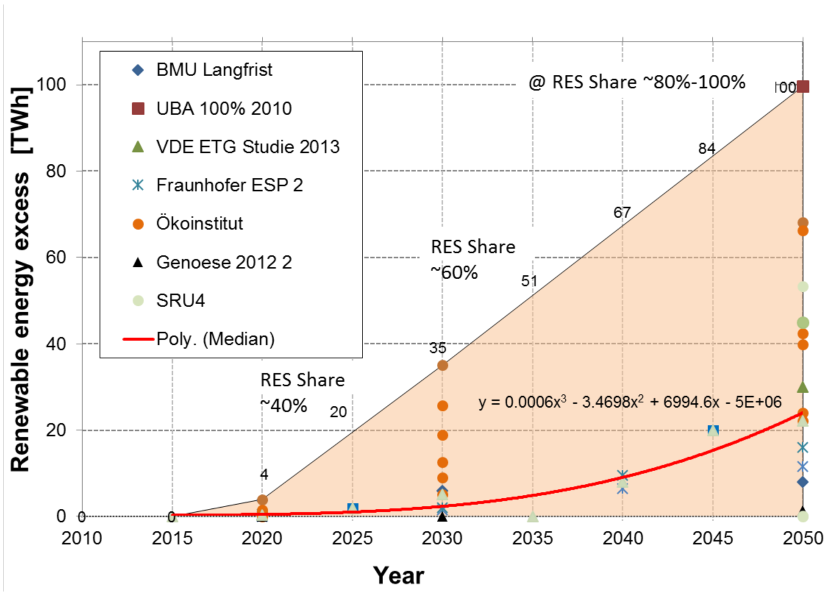

Figure 2-5: Comparison of different RES excess scenarios (own figure based on [48], [45] [2], [49], [33], [46] [47])

2.4 Future need for energy storage as a flexibility option

It must be stressed that energy storage is not the only available measure to facilitate RES system integration and to maintain system safety. Storage technologies make it possible to increase system reliability and flexibility by decoupling demand and supply of electricity in a time dimension. There are non-technical options available to increase system flexibility through regulatory or legal measures. Other possibilities are demand-side management or demand-side response measures where the provision of accurate information of consumer consumption behavior in combination with, e.g., dynamic pricing allows to remote control electricity load and devices to match current generation [50]. New flexible power plants (e.g., gas turbines, combined heat and power plants) provide most balancing power available nowadays [24]. Also, RES can be included in this category by adding the possibility of generation management to these (e.g., changing angles of wind turbines). Further measures from the supply side also include the conversion of synthetic fuels as H_2 or CH_4 which could be used for electricity generation. The electricity grid provides spatial sharing of flexible resources and represents thus an integral component of the future power system. Main options to increase grid capability are a) dynamic assessment of power transfer capabilities, b) expansion of the network (e.g., new AC or DC transmission lines), and c) power flow control [42].

All named options are seen a highly relevant for the future energy grid as only the conjunction of these allows a achievement of the German energy transition. The emphasis of this work lies on electrochemical energy storage technologies whereas more information about other balancing technologies is given in [24] and [42]. Energy storage can be categorized among the other options mentioned before as indicated in Figure 2-6 which also provides a brief description of these.

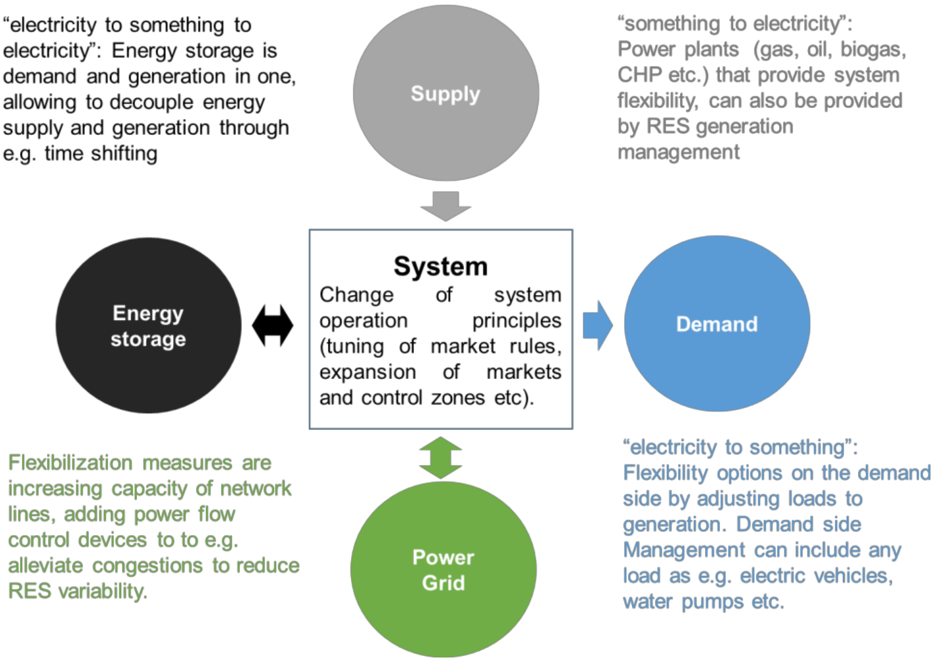

Figure 2-6: Overview of different flexibility options for RES balancing (based on [42] and [24])

As explained before, the need for electric energy storage is highly related to other developments in the energy system on a generation, grid, demand and system level. There is a high of energy system models available aiming to estimate the future demand for storage systems. These models mostly seek to achieve a macro-economic optimum of energy storage in relation to other balancing options, grid reinforcement measures and other factors by the use of mathematical optimization. Optimization goals in most of this assessments represent a minimization of overall system costs based on hourly time series [2], [32], [49]. These assessments often don´t allow a separated view on different storage technology types. Instead, generic technologies for power or energy applications are used due to practical reasons. Table 2-1 gives a brief overview of specific influence factors and system developments considered in such models that might reduce and stabilize or increase the need for energy storage technologies facing a high share of RES.

The literature points out that there is a difference between market and system based need for storage [51]. Both forms of energy storage demand can include in a simple way at least two application areas. These are namely:

a) Power applications with short periods of charge and discharge (milliseconds to minutes up to one hour) and many cycles a day [52]. Application areas in this time frame are balancing, power quality management and re-dispatch.
b) Energy applications including mid- to long term storage (storage time of several hours including multiple cycles per day) and long term storage (relatively long charging periods over days to weeks) to use the stored energy to decouple the timing of generation and consumption of electricity [53]. Typical business areas are electric time shift and RES support.

The need for energy storage from a market perspective arises in the case of negative wholesale market prices when supply surpasses the demand of electricity [48]. This situation can lead wholesale electricity markets to tumble, and spot market prices may spike. An explanation for this is the so-called merit order effect. Demand for energy storage out of a system perspective refers to grid congestions caused by, e.g. excess energy through RES. Such events occur when grid connection nodes cannot absorb electricity feed-in of generation units into the transmission grid level. Consequently, contracted energy cannot be physically delivered due to grid restrictions, grid errors or the breakdown of large generation units.

The market need for energy storage is mainly defined on the bases of arbitrage businesses on a transmission grid level (exceptions are Agora [54] and Grünewald [2]). Short-term services are mainly defined as applications with durations of up to 4 hours and mid-term storage applications with 8 to 10 hours [32], [49] and [55]. Additionally, the grid is modelled as a copper plate (see VDE –ETG [49], BMU Langfristszenarien 2012 [27], SRU 2011 [33] and Genoese [5]). The need for storage on a distribution or mid-voltage grid level is thus often expulsed as it is difficult to make robust prognoses in this field [56]. Redispatch[9] and frequency regulation are consequently also often excluded and only discussed qualitatively. Only a few studies consider this systemic benefits (category A / power applications) through energy storage as [51]. The “Roadmap Speicher” [51] uses adopted RES scenarios from [27] within the European grid. In this way interconnectors and supranational electricity trade is represented within the

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[9] Measures to mitigate grid congestions (e.g. violation of n-1 principles) by changing power output of local generation portfolio

simulation. The estimated German RES share is 45 %[10] for 2020 and 69 %[11] in 2030. EU shares are 26 % and 37 % for the EU in 2020 and 2030. Re-dispatch is simulated by adaption of the generation portfolio in a specific grid section via Security-Constrained Optimal Power Flow (SCOPF). It represents a linear optimization with the aim to minimize overall re-dispatch costs, based on the hourly status of the grid and market-based energy storage. A side condition of the linear optimization is the adoption of the feed-in rate of reactive and active power and transformer adjustment levels to avoid off-limit conditions and n-1 violation. The study calculated that balancing options with a total capacity of 2.400 MW could help to reduce re-dispatch costs up to 30 % and that they can help to facilitate a safe RES system integration until 2030 [51].

Table 2-1: Summary of system development that influence the need for energy storage technologies [57], [32], [2], [58], [55], [49])

Demand for storage	**Generation level**	**Grid level**	**Demand side**	**System level/ Markets & regulation**
Increased + ↑	1) Positive development of RES 2) Remaining share of must run capacities 3) Forecast errors of RES 4) Share of inflexible power generation[12]	1) Delay of grid reinforcement 2) No extension of inter-European grid connection points	1) Inflexible demand 2) No demand side management 3) Increase of demand	1) Increasing electricity & fuel prices 2) Support schemes 3) High CO$_2$ costs 4) Capacity markets
Stable or decreased – ↓	1) Use of flexible generation 2) Reduction of forecast errors 3) Reduction or retrofit of must run generation 4) Management of RES	1) Grid reinforcement 2) Increasing inter-European grid connections	1) Use of flexible consumers 2) Activation of de-mand side mana-gement in power markets 3) Decrease in demand	1) Low wholesale energy prices 2) Low consumer and electricity prices 3) Low CO$_2$ costs

The VDE – ETG Taskforce for Energy storage [49] estimates in their main scenario E that the German demand for short-term energy storage (< 4 hours) in 2050 could be up to 14 GW with a needed capacity of 70 GWh based on a cost optimum. The optimum short-term storage capacities from Agora 2014 [32] are vast (1 to 26 GW). Both [49] and [32] include extreme scenarios where energy storage is used to mitigate any excess energy from RES (over 25 GW in 2050). They also state that these scenarios are not economically viable. Scenarios between Zerrahn and Shill 2015 [57] are more moderate with low variations in the amount of excess energy is not considered as that high. All scenarios have in common that short-term storage take-off is estimated around 2035 when an RES share of 60% is achieved (see red line in Figure 2-7 A) due to the extrusion of residual load power plants through RES. Only few additional storage capacities of an average of 2 to 3 GW are required before 2020.

The need for long term storage (8-10 h) demand is higher in relation to short-term storage as depicted in Figure 2-7 B. The VDE – ETG Taskforce [49], Genoese [2], calculated an average need of 18 GW and 7 TWh storage capacity [34]. Droste-Franke [24] (not included in the graph) reports that

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[10] The scenario is divided into two wind capacity paths; Wind (53 GW, 45 Offshore) and Wind+ (65 GW Onshore; 55 Offshore)

[11] This scenario includes two paths Flex and Flex+, the latter includes grid reinforcement measures and flexible demand

[12] So called “must run” generation unit as Nuclear or lignite fired power plants or non-manageable RES units

economically viable storage capacities in 2040+ could be about 15 GW. Scenarios within SRU 2011 [33] consider that electricity supply is covered by 100 % through RES in 2050[13] resulting in very high demand for energy storage technologies. The need for storage over time is comparable to short-term storage needs, with take-off at a share of 60 % share of RES. The higher amount of required midterm in relation to short-term storage can be explained through longer deviations in RES production that have to be mitigated. However, it is clear that energy storage will play an essential role for these applications in the future energy system.

Potential demand for storage capacities on a short- to midterm level are depicted in Figure 2-7 C. Bubble sizes indicate the required energy storage capacity in combination with required power capacity. Storage capacity is calculated based on the reviewed studies where enough data is available. The graph shows that studies vary significantly in the bandwidth of required storage capacities.

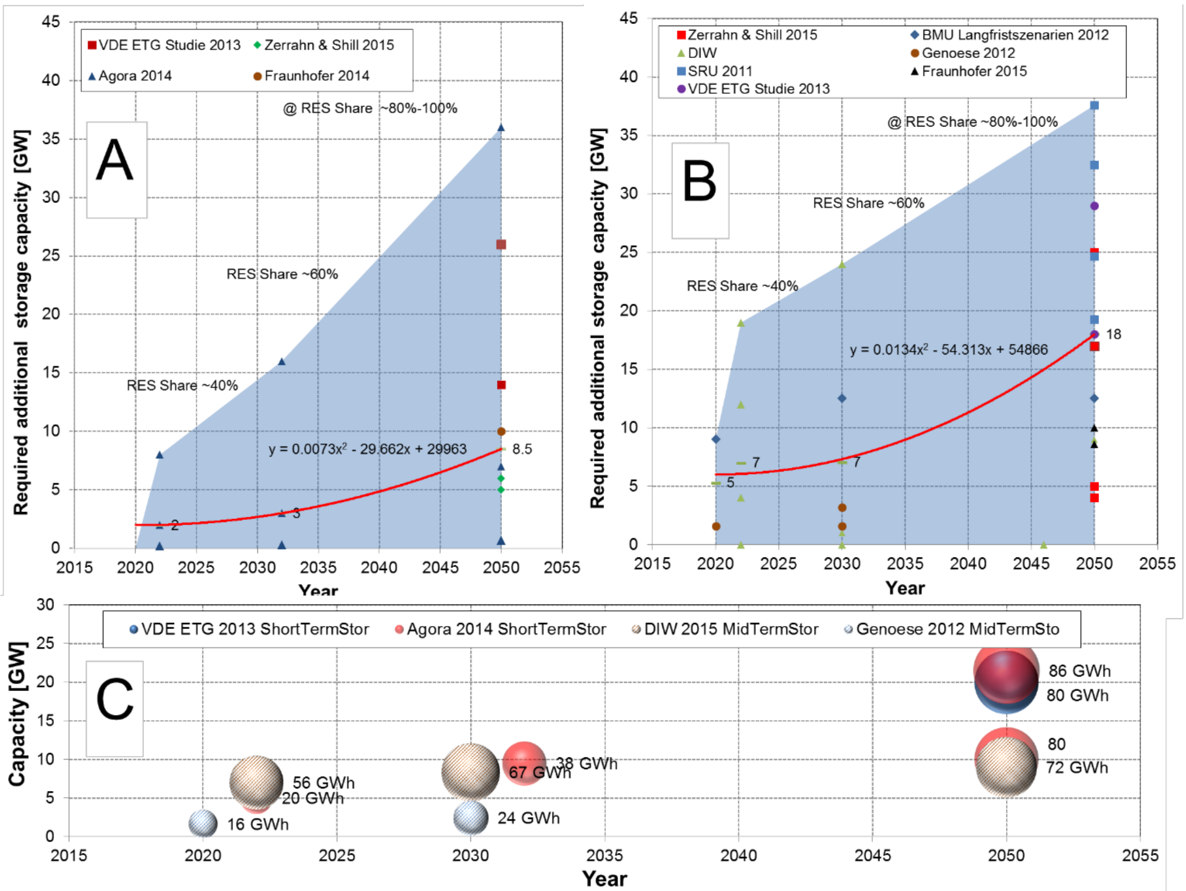

*Figure 2-7: **A**) Potential demand of short term storage power capacities (4<x<5 h per day) until 2050); **B**) Potential demand of installed mid-term storage capacities (8<x<10 h per day) until 2050 based on ([57], [32], [2], [57], [58], [55], [49]); **C**) Potential energy storage capacities until 2050 (own calculations based on [49],[57], [32], [2])*

2.5 Application cases for energy storage

Energy storage is seen as a valuable option to, e.g. facilitate a system integration of RES among other things by temporarily avoiding grid expansion investments or congestions in electric grids on all voltage levels, ancillary services, load leveling, voltage stabilization and system backup services. They have a

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[13] Scenarios 1 a, b consider only German RES generation units, 2.1. a and b considers a RES- connection DE-DK-NO, the last scenario includes full RES supply through a connection of north Africa to Germany (DE-EUNA)

highly vertically integrated nature due to the modularity of some technologies as batteries offering various services for the energy system including generation, network and demand within all voltage levels [59]. From this results a high number of potential users as well as business areas for (battery) storage systems distributed in the entire electricity system. Potential users-side actors are private and municipal utility companies, transmission and distribution system operators, end users (private households, industry), RES system integrators and manufacturers, pooled BEV-owners or third parties. Figure 2-8 provides an indicative overview of some application fields, their benefit type, typical power output and stakeholder groups affected by them.

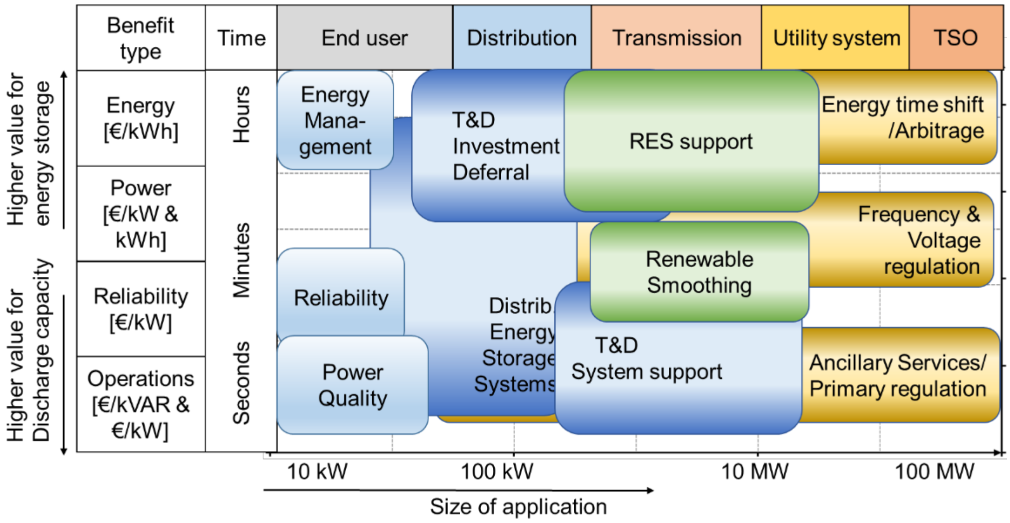

Figure 2-8: Indicative summary of different application fields for different flexibility options (adapted from [60])

Each application area represents a service provided by energy storage with a certain value. Energy storage technologies can provide multiple operational uses across the power system value chain. The aggregation of complementary benefits through the provision of multiple services is also named as “stacking” [60]. Some of the most named applications named literature and in Figure 2-8 are summarized in Table 2-2.

All named application fields exist today, and more will emerge in the future which will be part of future research [60]. More information about different application cases can be found in the given sources. Table 2-2 is not comprehensive; there are more relevant applications for energy storage in, e.g. stand-alone electricity systems in rural areas or mobile services [32]. For instance, uninterruptible power supply is one of the leading markets for battery energy storage nowadays (market size about 2 billion € in the EU), which is mainly triggered by the telecommunications sector [32].

Table 2-2: description of different energy storage application fields

Service	Description	Source
Balancing services: frequency regulation services and ancillary services	Match generation and load on a sec. to minutes Remunerations for being kept online and for providing energy. Primary, secondary and tertiary regulation (PRL, SRL and TRL)	[60], [61] [62], [63] [64], [32].
RES support: RES direct marketing, renewable smoothing	(EEG) obliges operators of large wind turbines to sell their produced electricity on wholesale electricity markets Mitigating effects from forecast deviations and exhausting arbitrage possibilities in spot markets Mitigation of rapid output changes due to the intermittency of solar or wind-based generation.	[60], [65], [63], [64]
Energy management: Electric bill management or Self-consumption	Use of stored energy by end-use customers in conjunction with RES to reduce electric bills. Solar generated energy in combination with battery storage is seen as an economically viable application field.	[60], [65], [64], [63]
Electric time shift /Arbitrage	Electricity is traded at different spot markets for electricity Baseload energy is bought and sold during on-peak times Most common application field for energy storage today	[60], [63], [64]
Transmission and Distribution upgrade deferral (T &D upgrade)	storage is used to defer the need to replace or to upgrade T&D equipment or to extend the life time of existing equipment Electricity is stored in times without congestion and discharged in peak load periods or vice versa during high RES generation inputs	[60], [63], [65]
Distributed energy storage	Modular systems provide increased customer reliability, grid T&D support, and potentially ancillary services and RES support on a local level	[60], [63]

2.6 Electric energy storage technologies for the grid

Energy storage technologies can generally be divided into mechanical (Pumped Hydro-Electric (PHS), (adiabatic) Compressed Air Energy Systems (CAES), Flywheels, electrical (Super Conducting Magnet Energy Storage (SMES)), thermal and chemical systems (including Battery Systems and Hydrogen) as well as hybrid systems[14] [66] [67]. Total global stationary storage capacity nowadays is around 168 GW of which only 4% is based on electrochemical storage (see Figure 2-9). PHS with a share of 84 %[15] is the only commercially viable and available large-scale storage technology nowadays. There are only low CAES capacities available nowadays with <1 % (CAES Huntorf in Germany with 321 MW and 560 MWh and McIntosh USA with 110 MW and 2.640 MWh) [68].

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[14] Represent a combination of different technology types as LIQHYSMES (Liquid-Hydrogen-Super conducting magnet energy storage) for short and long term storage times

[15] There is a total capacity of 7 GW installed in Germany.

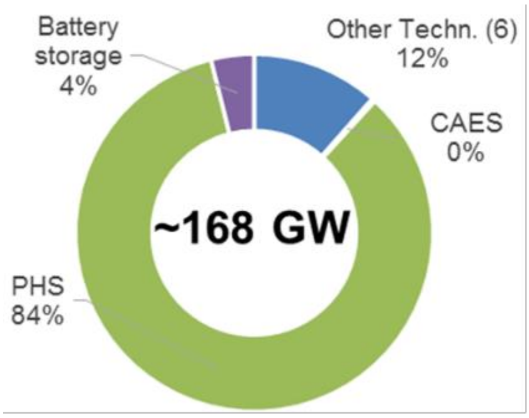

Figure 2-9: Total share of different electric energy storage technologies in 2016 (own figure using data from [65] and [69]

All storage technologies can be categorized in specific application fields in respect of their typical size and storage time which are namely: short-term storage from milliseconds to hours, mid-term storage up to 8 hours and long-term storage including several days up to weeks [48]. These application possibilities have different cost and technologic properties, which profoundly affect the applicability of different storage options when compared to the application fields in Figure 2-8. Figure 2-10 gives an overview of different storage technologies and operating ranges in respect of discharge time and storage capacity including Power to X. Comparable technology characteristics can lead to a competition between different energy storage technologies (CAES and PHS) as well as other flexibility options (e.g., CCGT). A further distinction of technologies can be conducted on the base of their location. Typical storage units nowadays are centralized storage units with a fixed location (e.g., CAES, PHS). They are often dependent on geographic aspects (e.g., height difference for PHE or salt/impervious rock caverns as wells as aquifers for CAES) and face acceptance problems [70]. A brief overview of the named technologies is provided in Table 2-3.

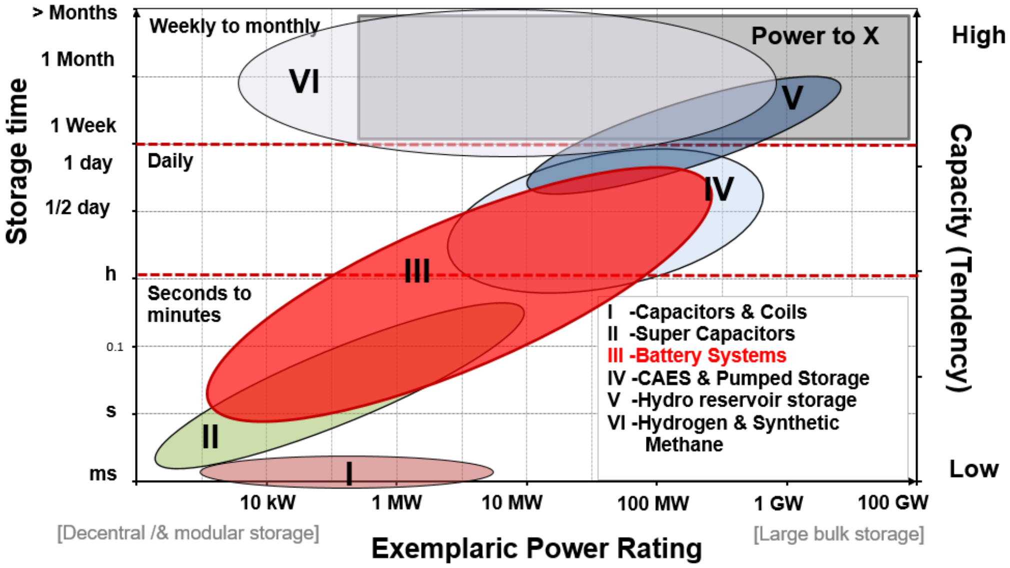

Figure 2-10: Comparison of different energy storage technology and their application fields (own figure based on [4])

In contrary decentral storage technologies as batteries refer to small and modular units that can be integrated into distribution grids, mid-voltage level or in local smart grids (e.g., battery systems in combination with multiple PV units and demand response). These technologies are told to have a comparatively little land use impact (e.g., land occupation combined with the removal of trees) and higher acceptance within society about centralized storage [71]. The modularity from some kW up to a multi MW level makes it possible to cover a full field of applications by adjusting the storage unit to potential changes, e.g. in a wind park (e.g., through repowering) and to adapt to new market situations. A significant problem of this modularity is that technology only benefits little from scale effects [48].

Table 2-3: Summary of different energy storage technologies based on [24]and [68].

Technology	**Description**
Capacitors	Electricity stored electrostatically between conducting plates separated by dielectric
Super capacitors	Comparable to capacitors but have a liquid electrolyte which forms a second plate of the capacitor
Compressed air storage	Energy stored in air compressed in high pressure (40-70 bars) in porous rocks, or salt caverns
Pumped hydro storage	PHS consists of two superficial water reservoirs situated in different altitudes (potential energy) connected by a penstock, turbines & generator.
Hydrogen & Synthetic methane / Power to X	Energy conversion into hydrogen (electrolysis) or in further step into, e.g. synthetic methane. Conversion to electricity through various technologies as gas turbines or fuel cells
Electrochemical storage/ batteries	Energy storage through chemical reactions

2.7 Electrochemical energy storage

There are several electrochemical energy storage technologies available for stationary applications nowadays. Figure 2-11 provides an overview of global markets for battery storage including the most installed types nowadays. High-temperature batteries, mainly through Sodium-Sulfur batteries (NaS) have the highest share in the segment (59%). Various Lithium-Ion batteries (LIB) also contribute increasing share with around 35 % followed by Lead-Acid based batteries (VRLA) and finally Redox-Flow-Batteries (RFB) with a 1% share. The market potential for electrochemical storage is seen as very high and could reach shares of up to 51% of total German storage demand in 2030 [72].

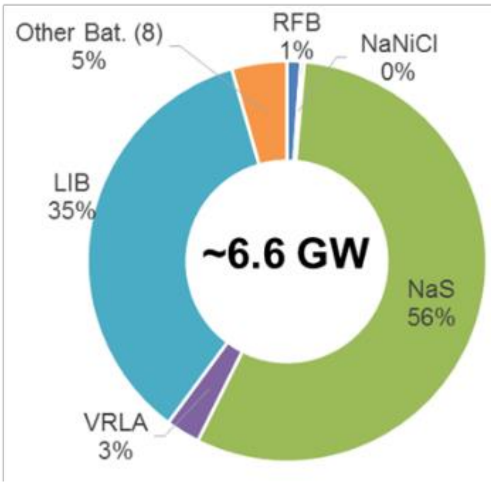

Figure 2-11: Total share of stationary battery storage and related shares of single battery chemistries in 2016 (own figure using data from [65] and [73])

2.7.1 Electrochemical energy storage technologies and properties

In general, cells can be classified into non-rechargeable primary cells, rechargeable secondary cells or tertiary cells which are fed continuously to the cell from outside [74]. A secondary battery cell consists of two electrodes (positive and negative), a fluid or gel-like electrolyte, conductor and a separator. The last-mentioned component is responsible for the separation of the reduction and oxidation processes, to avoid short circuits. When discharged, redox reactions occur at the electrodes causing an electron flow through an external circuit [59]. In more detail, electrons are released at the anode from the active material that is oxidized, and cathodic substances are reduced by receiving electrons [74]. After the battery is discharged an external voltage source forces a reversal of the electrochemical process (voltage ≥ as the equilibrium potentials of the two half cells). Through this process, the reactants are restored to their original form, and the energy can be used again by a consumer [74] [14]. A simple overview is the scheme of a battery is given in Figure 2-12.

There are several material combinations available for electrode design that can be used for electrochemical energy storage. The theoretical capacity and voltage of a cell are the function of the anode and cathode materials which determine the maximum energy that can be delivered by an electrochemical system. It is not possible to fully utilize theoretical energy storage capacity due to the need for nonreactive components as separators, containers, and electrolytes that add weight as well as volume to a battery. A detailled overview of different standard potential and capacity determined by the type of active materials contained in different battery cells is given in [75], [74].

Figure 2-13 provides an overview of the gravimetric energy density in Wh/kg and power density in W/kg delivered by different battery systems. The figure does not depict single values. Instead fields are plotted to demonstrate spreads of energy storage performance under different use conditions. The cycle and calendric life time (shelf time) of an electrochemical cell are beside energy and power density a vital parameter for economic and ecological reasons. The first refers to the number of cycles which determine how often a battery cell can be charged and discharged before a lower limit of nominal capacity is reached (a value of 80 % of nominal capacity is often set) [74]. Cycle life time is among other things a function of the depth of discharge (DoD) and is dependent on the used electrode material. A high DoD leads to lower cycle life times in relation to lower ones.

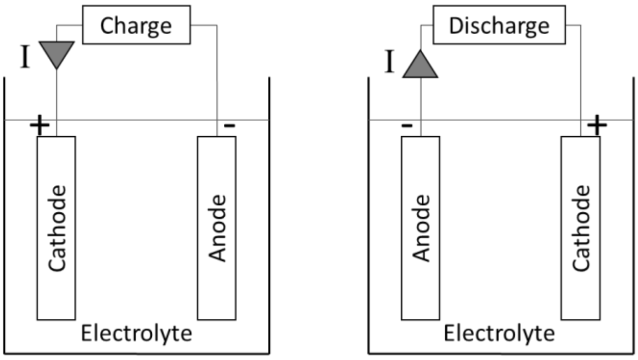

Figure 2-12: Simple scheme of a secondary battery charging and discharging (own figure based on [75])

Additional deterioration of secondary cells occurs through chemical side reactions which proceed during operation but also during mere storage time. These effects are dependent on the design of a cell, operation temperatures, the state of charge (SoC) affect the calendric life time and the charge retention of an electrochemical cell [74].

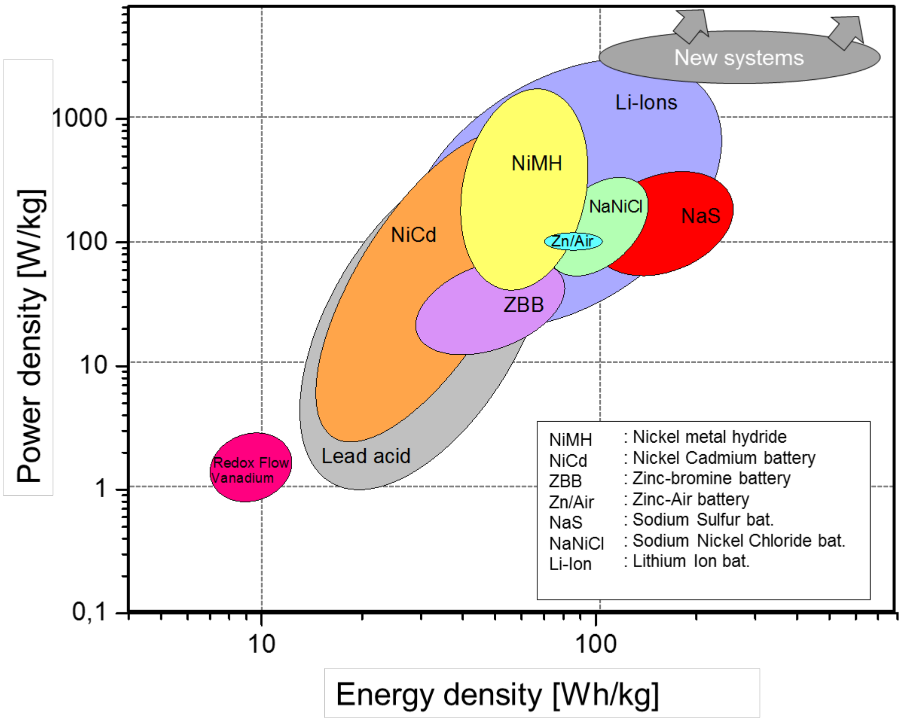

Figure 2-13: Ragone plot for comparison of energy storage properties of some different energy storage technologies (own graph based on Batt-DB)

An often named significant advantage of batteries in relation to other storage technologies is a high-efficiency grade (>0.6 up to 0.96) which represents the ratio of charged and discharged energy. The latter is always lower than the first due to incomplete conversion of charging currents and occurrence of side reactions with heat production. Naturally, this is dependent on the used electrode materials, formation as well as design and electrolyte conductivity [75]. Other influence factors to be named are temperature, current density, the porosity of the separator and the age of a battery cell [74].

Battery technologies can be considered as a relatively safe source of energy if they are operated properly. A precondition for safe and reliable operation is the choice of the right electrochemical system with correct charge, discharge, and other storage conditions. It is possible that batteries can rupture, vent or in extreme cases explode in case of extreme abuse (too high or improper charge or discharge rates, short-circuiting, too high temperatures) [68]. Every battery system thus inhibits a battery management system which is especially crucial for Li-Ion batteries [74].

A brief introduction to different battery technologies is given in Table 2-4. The list is not comprehensive but includes all technologies that have a particular market share nowadays.

Table 2-4: Summary of different electrochemical energy storage technologies (sources are provided in the table)

Technology	**Description**
Lithium-Ion batteries (LIBs)	Li-ion batteries are produced with various anode and cathode combinations resulting in different performance characteristics. The anodes currently use graphite or lithium salt of titanium oxide (LTO) as the active material. Cathodes active material can be Co-dioxide; Ni, Co, Al or Mn composite oxides; Mn spinel oxide or iron phosphate [76].
Valve Regulated Lead Acid Battery (VRLA)	Built out of a positive electrode of lead oxide and a negative electrode of sponge lead. The electrodes are separated by a microporous material and immersed in an aqueous sulphuric acid electrolyte [77].
Sodium Sulfur (NaS)	NaS- batteries consist of liquid electrodes and a solid electrolyte [4]. The cell voltage level is between 1.7 and 2.08 V at 350°C [71]. The main disadvantage is the requirement for a thermal management system [52], due to a very high required operating temperature to keep the electrodes above their melting point or liquidly respectively and to achieve an adequate ion conductivity [4] [60].
Sodium Nickel chloride	Also high-temperature battery (>300°C), with a secondary electrolyte of molten sodium tetrachloraluminate (NaAlCl4) and solid transition metal halides (FeCl2 or NiCl2) as active cathode materials [52], [78]. Less corrosive and safer reaction products than NaS [52], [71]
Vanadium redox flow (VRFB/RFB)	Battery systems in which one or both reactants (liquidized ionized metal compounds) are stored in external tanks while a stack itself contains the electrodes which are serving as reaction sites and current collectors. Electrolytes are pumped from the tanks to the electrodes (by flowing through porous diffusive layers made of materials such as carbon felt) within the cell [79] [80]. Nowadays the all-vanadium based RFB-system is the most developed RFB type and the only one that reached commercial fruition [79]
Others	All Ni-metal batteries (NiCd, NiMH), Polysulphide-bromide flow battery Zinc-bromine redox flow battery

Especially LiBs are seen as one of the most promising systems in development for the next 10-15 years requiring R&D programs to take profit of all its potentiality [81]. The reason for this successful development can be explained by their very high gravimetric and volumetric energy density, offering good competitive advantages on this market segment [59]. Further growth of the LIB-market due to electric transportation and consumer electronics may lead to further technology improvements and manufacturing economies of scale, which could also make electricity grid applications more feasible [52]. Experts believe that stationary markets for LIBs may exceed those for transportation [81].

2.7.2 Challenges and research demand for electrochemical energy storage

On the one hand, technologies as lead-acid batteries are in general a mature technology, which is utilized for more than a century for industrial products [81]. On the other hand, available battery technologies as Li-ion or redox flow batteries have many shortcomings in a variety of use cases. There is still high effort needed in basic research for market breakthrough regarding cyclic and calendrical life time, safety and environmental concerns for most technologies. A brief overview about significant research in the mid- to long term to come is given in Table 2-5. Battery research nowadays is a dynamic, active field with various involved institutions carried out on a global scale.

Table 2-5: Major R&D activities in the field of battery storage mainly based on [82], other sources are indicated in the table

Technology	Mid-term 5 to 10 years	Long term 10-20 years
Lead Acid batteries	Develop high-power/energy carbon electrodes, understand poor materials utilization through diagnostics	Develop advanced active materials can help to improve specific power and lower resistance designs [81]
Li-Ion batteries	Design and fabricate novel electrode architectures, New models for ion transport through solids Development of high conductive inorganic solid-state conductor for solid-state Li-Ion batteries	Develop new intercalation compounds with low cycling strain and fatigue; aim for 10k cycles @ 80% DoD Develop self-balancing chemistries to eliminate need for balancing electronics Develop high energy density electrodes with high ionic and electric conductivity
Sodium-based batteries / High-temperature batteries	Decrease operation temperature, near to ambient temperature Develop robust planar electrolytes to reduce stack size and resistance	Develop sodium-air battery which provides higher value in almost all categories of performance Identify species on sodium-ion anodes and cathodes
Flow batteries	Emergent research fields are the development of new electrolytes and the permeability of membranes, new cell designs, decreasing costs regarding membranes and stacks as well as the effect analysis of more extended non-service periods on electrodes [3].	Develop non-aqueous flow battery systems with broader cell operating voltages to improve efficiency

A major problem of battery technologies are high capital costs in combination with long amortization periods lead to accordingly high risks for investors and can be seen as a main barrier for further diffusion from an economic perspective [83]. Economies of scale through electric battery vehicles roll out can help to overcome some obstacles by the use of cheap materials and production strategies and new electrolytes.

There are several stages of battery life cycle including production, use, and disposal in which negative effects on the environment cannot be avoided completely. There are for example heavy metals like copper, nickel or cadmium as well as other toxic organic compounds that can be contained in certain battery systems and related electronics. Especially the disposal of “newer” battery technologies as Li-Ion batteries is thus still a challenging task [84]. The growing demand for electrochemical energy storage and resulting mass production also increases resource depletion of rare earth, metals, and other materials. All these factors lead to a higher awareness of environmental problems caused by battery technologies and might result in stricter regulations, especially on those which are related to hazardous residues containing heavy metals [85]. A prominent and often cited example here fore is the development of the nickel-cadmium battery (NiCd). The application of NiCd batteries in Germany is limited to medical and security-related areas as well as electric vehicles due to the EU-wide restrictions of cadmium use since 2006 [86]. Such examples show the importance of approaches as LCA to identify potential environmental impacts in advance that might lead to a restriction of the use of technology as in the case mentioned before.

Not only environmental and techno-economic issues can hinder the market diffusion of electrochemical storage. The commercialization of various battery technologies is also highly dependent on policy facilitation which will be crucial to the uptake of grid-scale, residential-scale and electric vehicle battery technology over the next decade [87]. Such facilitations are, e.g. proper market regulations, safety and recycling frameworks and grid integration rules. An overview of different support policies which include efforts such as financial support for R&D, market transformation and mandates for projects can be found in [69].

2.8 Decision support on energy storage and other flexibility options

The studies analyzed in the chapters before showed in a technology agnostic type that there is a potentially high demand for additional energy storage capacities to flexibilize the power system of the future. It remains unclear which technologies will be suitable for these tasks and to which services they will provide. The following chapter provides a brief introduction to energy storage criteria which are used to compare and evaluate different technologies. The emphasis lays especially on multi-criteria decision analysis (MCDA) which is told to provide decision support through the ranking of technologies based on a certain set of pre-determined criteria and a wide set of available methods.

2.8.1 General requirements on energy storage technologies

Energy storage technologies have to face different and often competing requirements which are dependent on the viewed application field. An optimization of, e.g., battery energy density might lead to losses in power density whilst increasing cycles might lead to higher cost. Every technology has to fulfill simultaneously multiple performance requirements such as high power, high energy, long life, low cost, excellent safety, abuse-resistance, a wide bandwidth of operating temperatures and minimal environmental impacts. Nowadays no technology can meet all of these goals, making the right decision of a proper battery system for an special application often a compromise [74]. The choice of the best energy storage technology is always based on the requirements of a certain application field. It is possible to define favorable properties for energy storage which are provided in Table 2-6.

Some of the named properties for energy storage technologies named in the table above are given in Table 2-7. The values provide bandwidths of major energy storage characteristics, which gives an impression about the high variance of a selected set of important properties. Each application field has certain requirements on the characteristics depicted in Table 2-6 which have to be matched with the properties of energy storage technology.

Table 2-6: General requirements on energy storage technologies based on [74] and [88]

Aspect	**Attribute**	**Description**
Quality of storage	High energy density	Ability to store energy per mass or volumetric unit
	High Power density	Ability to provide high charge and discharge rates
	Low self-discharge rate	Rate of energy losses over time
	High-efficiency grade	The ratio of output to input energy
Safety	High operation safety	Low probability of fire, explosions,
	Low damage potential	Damage though, e.g. toxic materials, explosions.
Life time	High calendar life time	Low rate of electrode degradation over time
	High cycle life time	Number of deliverable charge-discharge cycles
Environmental compatibility	Production	Energy demand, emissions and
	Use	Efficiency grades, consumption of power
	End of life	Toxic materials, recyclability of used materials
Economic	Low investment cost	Includes all cost for uptake of a storage project
	Low operation cost	Includes all cost related to maintenance, electricity/fuel purchase
	Low cost per stored watt-hour	Cost of battery and ratio of charging cost to delivered energy

Table 2-7: Overview of different balancing options median and lower quartile values using values from [89], [90] and [91]; [92], [93], [94], [95] and [96], [92], [97], [98].

Technology	**Efficiency**	**Energy density**	**Power density**	**Cycles**	**Life time**	**Investment cost (cell)**
	[%]	**[Wh/kg]**	**[W/kg]**	**10^3**	**[a]**	**[€/kWh]**
All Vanadium redox flow	66-75-85	8.7-10-21	1-1.6-2.1	9-10-13.3	6.3-15-20	129-458-860
Li-Ion (various)[16]	81-91-98	84-115-145	253-640-1,300	0.73-2-8	7.5-15-20	453-745-1,227
Lead Acid[17]	63-76-90	23-33-37	3-27-53	0.3-1.6-1.8	10-18-20	179-230-320
High temperature (various)[18]	75-86-90	120-148-158	113-160-196	2.8-3.6-5.9	10-14-17.5	172-295-440
Ni-based[19]	60-81-85	58-57-46	140-186-477	0.8-1.6-2.5	7.1-12-13	290-1,200-2,300
Pumped hydro storage	65-75-85		0.5-1-1.5	10-16-50	30-40-60	46-500
CAES	54-70-88	3.8-5-6	-	6-12-20	20-35-40	3-40-300
CCGT	54-60-63	-	-	-	20-30-40	680-900 [€/kW]
SuperCaps	90-95-97.5	5.2-8.7-21.7	1.450-3,500-1,0000	21-50-100	10-15-20	570-1,463-6,800

2.8.2 Socio-ecologic and economic requirements on energy storage technologies

The work of [99] represents a socio-ecological analysis in combination with potential acceptance problems of decentralized battery storage technologies in distribution grids in the frame of the German energy turn-over. An online survey was conducted for three different community types across Germany namely communities with; A) high activity in the field of RES B) considerable activities in the field of RES and C) low activity in the field. A total number of survey participants was 11,191 residents. The results

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[16] Summary of LFP, NCA, NMC, LTO, LMC without peripheries (inverter, balance of plant etc.)
[17] Summary of VRLA and Flooded Lead acid batteries (inverter, balance of plant etc.)
[18] Summary on NaS and NaNiCl batteries (inverter, balance of plant etc.)
[19] Summary of NiCd and NiMH (inverter, balance of plant etc.)

of this work indicate a high acceptance of battery storage technologies in general in comparison to other flexibility options. Potential characteristics which might lead to lower acceptance of different electrochemical storage technologies were also assessed. The author made a significant distinction between social aspects and environmental aspects relevant for energy storage acceptance. Participants then could express their preferences on a Likert scale (1 - low to 6 - high). In case of the first aspect, the criterion of “no impacts on human health” was ranked the highest followed by “safe electricity supply” and “no danger of fire or explosions.” Relevant criteria related to environmental aspects are “emission-free,” “low degree of ecological impacts,” “environmental impact” and “long life time”.

Another example is the work of [100] which also carried out an online survey about the energy turn-over with 108 participants in the community of Grafing - Bavaria. Citizens were asked to rate the importance of different aspects seen as relevant for integrating energy storage technologies into the community’s power grid. The majority of habitants (70%) thought that it is crucial that local energy supply is supported, followed by the reduction of CO_2 emission (52%). Interestingly the reduction of the nuclear power share (36 %) played a more important role than the positive economic effect on end-users [100]. One section within the same work was concerned about preferred characteristics that an energy storage technology should have out of the community’s perspective. The criterion “No impact on nature and landscape” was ranked the highest (74), followed by “environmentally friendly” (70) which seems to be a rather redundant result.

Results of both surveys are provided in Table 2-8 and give an impression about the relevance of different technology characteristics related mainly to battery storage or decentral storage based on [99] and [100].

Table 2-8: Summary of the preferences of different community residents in Germany regarding social and environmental aspects for socio-ecological acceptance based on [99], ComI=community with high activity in the field of RES. ComII=Community with considerable activities in the field of RES; ComIII=Community with low activity in the field of RES N=11,191 where 1 is low relevance and 6 very high, Relevance of different storage characteristics for Grafing – Bavaria based on [100], numbers indicate the amount of votes for one option

For battery storage [99] **N=11,191**				*Storage in general [100] with N=108*	
Socio-economic aspects	**Com. I**	**Com. II**	**Com. III**	**Socio-economic aspects**	**Responses -%**
Low cost	3	3	4	No impact on nature and landscape	74
No impacts on human health	5	5	5	Environmentally friendly	70
Safe electricity supply	4	4	5	Sufficient for energy autarchy	65
No danger of fire or explosions	4	4	5	Sub-terrainial location	30
No impact on landscape	2	2	4	Outside the city	18
Environmental aspects				Small size	17
Low demand for space	3	3	5	Small impacts during constr.	15
No noise	5	6	6	Short construction time	12
Low efficiency losses	5.5	6	6		
Emission free	6	6	6		
Low degree of ecological impacts	6	7	7		
Long life time	6	6	6		
High recycling rate	4.5	6	6		

None of the mentioned studies provides an evaluation of different storage technologies based on the obtained values to provide decision support. In some cases, chosen criteria seem to a certain degree to be redundant. Conducting simple weighting without an overlying heuristic which, e.g. allows to include cognitive abilities of a decision maker or depicting consequences of preferences inhibits the danger of providing biased findings. There is furthermore no detailed distinction between different application cases for technology. Results of the studies presented here nevertheless provide a valuable indication of the relevance of different aspects of energy storage choice, design and development.

2.8.3 MCDA studies for batteries and other flexibility options in energy systems

Multi-Criteria Decision Analysis models (MCDA) as a sub-discipline of operations research explicitly consider complex decision problems and provide a possibility to tackle them [101] and to unveil stakeholder preferences in a formalized and reproducible way. A literature review of MCDA studies was conducted to get a first overview of relevant criteria and methods that are considered as necessary for the evaluation and choice of energy storage technologies. The review was limited to publications within the field of energy systems, RES and storage. MCDA methods have already been widely applied to solve large-scale socio-technical decision problems with intangible an tangible criteria according to energy policy planning as in the case of Finland [102] or for the choice of the best renewable energy technology for sustainable energy planning [103]. The review shows that most MCDA studies claim to identify the most sustainable energy technology based on mainly four dimensions: technological, environmental, economic and social criteria [11] [104].

These four main aspects comprise a high number of sub-criteria. A summary of multiple sub-criteria used in MCDA literature regarding different energy systems can be found in Table 2-9. Only a small number of the reviewed publications focus on balancing and energy storage technologies. These studies are additionally summarized in the same table in the column Energy storage systems (EES) to get an overview about specific criteria used to evaluate these technologies.

Economic criteria include aspects as costs and profitability as well as methods (e.g., payback method or NPV). The most named criteria in this area are Life-cycle-cost (LCC), levelized cost of energy, investment costs and operation and maintenance costs. This comes true for energy systems in general and energy storage in detail. Other named factors for storage are, e.g. export potential or emission costs. It is in some cases challenging to separate economic factors from social ones, as, e.g. a high export potential may create jobs leading to higher social standards [104].

Environmental criteria consider various specific emissions of electricity generation or other indicators also used for LCA. Prominent criteria here are land use, greenhouse gas emissions, and resource depletion. The latter is the most cited one for energy storage. There are some other aspects named as water pollution or wildlife impacts in the context of energy storage [105].

Technological aspects are often used to analyze the general suitability of technology for a particular application field. It is difficult to really separate technology aspects from, e.g. economic aspects as the one influences the other. Efficiency, maturity and system life are in general considered as relevant. More clear criteria as cycle life time or power and energy density are included in the case on energy storage [106], [105].

Relatively “new” are social aspects which include factors as acceptance, impact on human health or job creation effects [104]. The latter is considered as very important in most reviewed studies followed by social acceptance and effect on the landscape. Some of these criteria can be to a certain degree redundant and difficult to measure. Social acceptance was named the most for energy storage [107].

Table 2-9: Review of criteria used in MCDA literature for energy system evaluations (partially based on [8])

Aspects	Criteria	Literature for energy system evaluation	Σ	EES	Other EES criteria
Environ mental impacts	Resources	[104], [103], [108], [107], [109], [105]	5	3	Water pollution, Wildlife impacts [105]
	GHG emissions	[104], [110], [103], [111], [112], [107]	5	1	
	Impact on ecosystems	[103], [107]	2		
	Risk in cause of failure	[107]	1		
	CO2 Emission	[103], [113], [109]	3		
	CED	[104], [114]	2	1	
	Land use	[104], [113], [110], [111], [112], [115], [105]	6	1	
	SO2	[109]	1		
	NOx	[109], [114]	2		
	Particles	[114]	1		
	Others	[111], [112], [115], [107], [105]	3		
Eco-nomic aspects	Specific cost, LCOE, LCC	[113], [107] [109], [110] [114], [112], [115], [116], [106]	7	2	Export potential, [104], End of life costs, emission cost [105]
	Enh. Of comp.	[107]	1	1	
	Investment Cost	[103], [113], [109], [114], [111]	5	3	
	O & M Cost	[103], [105]	1	2	
	Fuel Cost	[111], [105]	1		
	Payback method	[103], [117], [111]	3		
	NPV	[111]	1		
	Others	[107], [110], [114], [103], [111], [105]	5		
Social aspects	Compliance with pol goals	[104], [107]	2	1	Security [105]
	Nat. indep.	[107]	1	1	
	Employm. Pot., new jobs	[107], [109], [117], [111], [112], [115], [105]	6		
	Social accept.	[103], [104], [107], [111], [115], [105]	5	2	
	Effects on landscape	[107], [110], [107]	2	1	
	Social Benefits	[103], [111]	2		
	Risk	[104], [115]	2	1	
	Contribution to reg.dev.	[117]	1		
	Other	[110], [114], [105]	2		
Tech-nology	Efficiency	[113], [104], [107], [114], [117], [111], [116], [106], [105]	6	3	Production Energy density, Load response, [116], Capacity, power density, cycles [105]
	Exergy efficiency	[108],	1		
	PER	[108]	1		
	Safety	[111]	1	1	
	Reliability	[103], [110], [111], [116]	3	1	
	Maturity	[103], [116], [110], [117], [106], [105]	4	2	
	System life	[111], [116], [118]	1	2	
	Availability	[111]	1	1	
	Fatalities	[112]	1		
	Flexibility	[115], [116], [105]	1		
	Others	[107], [110], [112], [115], [116], [106], [105],	4	3	

The literature review revealed that there is a high number of publications concerned with the issue of sustainability of energy technologies including a manifold of different indicators and methods. There are, however, only a few studies that have a direct focus on energy storage in general or more specific on electrochemical energy storage. In total only following studies were found that explicitly address energy storage or balancing options [116], [104], [107], [106] and [105]. The named studies are summarized in Table 2-10 including the assessed technologies, used MCDA methods, aim of the study and its results in the form of different rankings. The studies are also briefly analyzed regarding the expert consultation for weighting of criteria. Criteria used for the different evaluations are indicated in Table 2-9.

The comparison of named studies gives interesting insights into the diversity of results in a frame of comparable goal settings but different application areas. In Daim et al. [105] CAES was evaluated as the best energy storage technology regarding RES integration and sustainability. Batteries (NaS) were ranked second followed by PHS the as the worst alternative. The weighing was conducted on the base of 12 expert opinions. Environmental impacts (air and water pollution and wildlife impacts) have been evaluated by three expert opinions from Bonneville Power Administration, which is the home institution of two of the co-authors. Other criteria have been evaluated on the base of literature.

Krüger et al. [107] use a mixture of qualitative and quantitative approaches to evaluate technology based on criteria which are then transformed into to a 0 to 10 scale for further calculus. Indexing is based on own estimations based on literature (comes true for storage technologies) and partially own calculations (LCA and economic modeling) for some of the assessed alternatives. There is no distinction between different use cases for using technologies (cost is evaluated on a 6-hour use case whereas environmental evaluation is based, e.g., for Redox flow batteries on energy to power ratio of 8). Detailed information on score attribution through literature are given. Grid extension measures are ranked first, batteries and CAES last. The attribution of weights within MCDA (Analytical Hierarchy process AHP) was conducted by the project team itself.

Energy storage evaluation in Barin et al. [106] is conducted on the base of three different scenarios; a) power quality, b) cost scenario and c) environmental scenario where a) is used as base scenario. Batteries (Li-Ion and V-Redox-Flow-Battery) are ranked best, and PHS worst in the central scenario a. Flywheels are ranked first in two alternative scenarios. A set of researchers from the same university carried out a qualitative evaluation from 1 to 10 of a set of criteria as “load management,” “technical maturity” and “environmental impacts”. Quantitative factors are, e.g. efficiency and cost per kW.

Oberschmidt [104] evaluates three different storage technologies via Promethee I using different technology evaluation scenarios which are dependent on the specific grade of maturity of each assessed technology. Results, including a comprehensive sensitivity analysis, show that RFB is ranked first and adiabatic CAES (here named as TACAS) second whereas Proton Exchange Membrane used for H_2 production with re-electrification with a gas motor is ranked last. No stakeholders have been included in the weighting process of this work, instead, literature values are used. Nevertheless, the inclusion of stakeholders is comprehensively discussed including ways of achieving consensus among stakeholders.

The work of Raza [116] considers H2-fuel cells as a best alternative. The method is based on indexing on a scale from -5 to 5 of different properties. Criteria are classified based on calculations (cost based on net present value) and own qualitative estimations of all other criteria through authors about, e.g., “*environmental impacts*” and “*risk factors*” named in literature. There is no interaction with stakeholders during the assessment.

The contradictory results of the reviewed studies make it difficult to identify the best alternative of technology to enable a sustainable energy system. This might, on the one hand,, be based on the specific use cases they allocate to different technologies. On the other hand, and maybe more severe for some of the outcomes, is the degree of representativeness and high subjectiveness of obtained weights through a low number and homogenous selection of experts. Not all studies consulted experts as [116] and [104], which are only partially comparable due to the different technologies that were taken into account. Studies where experts were consulted hardly give information about the kind of inquiry, number of participants or the procedure of weighting in general as in [107]. It seems that additionally the number of participants was rather small and homogenous as in [105] and [106]. The choice of criteria in most studies is based on literature and a selection process conducted through authors. Thus, all studies have their shortcomings which comes especially true when it comes to the selection of stakeholders.

Table 2-10: Comparison of MCDA literature concerned with energy storage or balancing technologies in general

Source	Technologies	MCDA Methods	Aims and Results	Experts	Comments
Daim et al. [105]	PHS, CAES, NaS	AHP, Fuzzy Delphi, fuzzy consistent matrix	**Goal:** Choice of reliable and cost-effective storage option for US regarding RES **Result:** 1st CAES, 2nd NaS, 3rd PHS	Interviews with Bonneville Power Admin. Experts, no of consulted interviews unknown	Based on expert interviews, Results flanked with sensitivity analysis, technology evaluation based on qualitative estimation
Krüger et al. [107]	PHS, Hydrogen, V - Redox Flow Battery, NaS, CAES grid reinforcement, measures: DC underground cables & overhead lines, High temp. Transmission lines	AHP	**Goal:** Find most sustainable way to use excess wind power **Result:** 1st – 4th Grid reinforcement, 5th new PHS, 7th to 10th PHS and Hydrogen, 11th AC underground cables, 12th H2, 13th to 14th batteries, worst on place 15 CAES	Unknown, no information given, only refer to "decision maker"	Quantification through indexing and aggregation of properties and own calculus, Results are seen as consistent for grid measurements, Storage technologies except CAES are seen as no alternative
Barin et al. [106]	CAES, PHS, H2, Flywheels, Supercap. Li-Ion, NaS, V - Redox Flow Battery	AHP and fuzzy logic	**Goal:** Find most suitable Power Quality alternative in combination with RES **Result:** 1st Li-Ion & Flywheel, 2nd NaS, VRB and H2, PHS & CAES on 4th rank	Num. of participants unknown, group of researchers from Fed. Univ. of Santa Maria	Based on literature review, only 2 quantitative factors (eta and cost), rest is qualitative, consistency measure unknown
Ober-schmidt [104]	V - Redox Flow Battery, Fuel Cell (PEM), TACAS - Thermal and compressed air storage	Promethee	**Goal:** identify most suitable long-term storage option for RES **Resul**t: 3 Scenarios – overall result 1st V - Redox Flow Battery, 2nd TACAS, 3rd fuel cells (H_2)	No experts, based on Literature and database: "Multidi-mensionale Technikbewertung "	Chapter within a PhD, very comprehensive work – considers only long-term storage, good understandable framework
Raza et al. [116]	Lead Acid, Li-Polymer and Fuel Cell (PEM) – H_2	Index based approach	**Goal:** Find best sustainable option for intermittent RES (PV) **Result:** 1st Fuel cell, 2nd Li-Ion and last Lead Acid 3rd	No experts, calculated on base of a developed sustainability index	Reasoning for quantification (e.g. efficiency and cycle life time) remains questionable, dubious sources

2.9 Summary and implications for research

The German power grid will be strongly shaped by a high share of RES of up to 100 % in 2050. Several studies point out that there is a need for additional balancing capacities due to excess power through RES between 0 up to 100 TWh in the same year. These demands are seen in a magnitude of 0 to 35 GW for short term storage (up to 4 hours) and 0 to 37 GW for mid-term storage (>8 hours). This development is also told to be accompanied by a stronger decentralization of generation and a more complex structure of the power grid. Contrasting these expected developments with a historic perspective shows that in general the development of the power system influencing the market uptake of energy storage can represent a complex interplay of policy, societal demands towards a greener electricity generation, utilities, technologies, and research.

Energy storage is just one available flexibility option among demand side management, electricity grid extensions, power plants with high power gradients, market and regulation measures. It is possible to characterize energy storage into centralized (PHS, CAES, etc.) and modular/decentralized technologies (battery storage, supercapacitors etc.). Electrochemical energy storage technologies can be allocated to the latter and include a high amount of differently available cell chemistries. NaS, Li-ion, Lead Acid, High temperature and Vanadium Redox Flow batteries are the most used technologies for stationary applications nowadays. Market development of stationary battery storage technologies in Germany is expected to grow from up to 59% in 2030. There is further research needed for market breakthrough regarding cyclic and calendrical life time, safety, environmental concerns and mainly investment costs. Another critical factor is the availability of suitable market and regulatory framework for energy storage. This comes primarily true when electrochemical storage is compared with other balancing options as CAES, PHS or CCGT.

Literature states that the demand for energy storage technologies in various application fields (ancillary services, energy management etc.) will potentially increase sharply starting in the 2035ies. Reviewed studies use technology agnostic approaches or only a limited set of technologies to estimate future energy storage demand. This approach is sufficient to provide more extensive insights of potential interrelations and developments of storage and the energy system in general but provides only limited decision aid for the selection of a technology for different power grid services.

Sustainability is considered as a significant aspect of the choice of the right energy storage technologies. Some studies give general insights of actor notions about the importance of criteria in this context relevant for energy storage but do not quantify these. Criteria evaluation is conducted in a somewhat non-formal way using a Likert scale approach. Furthermore, a pure “end-user perspective” is given, as their research is centered on acceptance. There is no industry perspective given which might indicate reasons to invest in energy storage. It is assumed that participant’s knowledge about energy storage technologies is relatively low as the technology has a comparably low market share nowadays

Literature including MCDA also provides a broad set of methods and criteria for energy storage evaluation and selection. These are often declared as sustainability criteria which are mainly structured around technology, economy, social aspects as well as environmental impacts. The term sustainable often remains undefined and blurry. Most of the studies use mixed qualitative and quantitative approaches for criteria aggregation, often by the use of indexing of properties of defined scales (e.g. -5 to 5) which can be seen as a source of uncertainty due to different notions about specific impacts which may lead to inherent decision conflicts (e.g. social impact vs. economic performance). Values used for technology evaluation are, despite some exceptions, mainly based on literature sources or on the base of expert opinions. Experts in these studies seem to be mainly centered in the same technological field (e.g., stakeholders from a utility or academia). At least in the considered studies, there seems to be an absence of a heuristic for stakeholder inclusion when it comes to technology evaluation and selection.

Besides a missing heuristic for stakeholder inclusion, only some authors conduct own calculations and instead rely on specific literature in the field. Such comparisons may be based on using environmental impacts calculated for a certain application and costs calculated in a different context and can be seen to a certain degree as inconsistent. Beside this different system, boundaries are used in different literature sources which furthermore increases uncertainties when it comes to criteria aggregation. Additionally, all studies do not consider the interplay of different stakeholders or significant socio-technical dynamics and interrelations as well as potential impacts on actor notions of what is claimed as “sustainable.”

There also seems to be an absence of approaches that enable social learning on multiple levels between different actors when it comes to enabling technologies. Such approaches have to engage the community and make it possible to think through the kind of future they aim to achieve. At the same time, such a process has to be open enough to avoid the creation of paralysis in situations with different views about values. Instead, they have to use constructiveness that allows diversity of opinions to be expressed [7].

3 Theoretical background

Technology assessment (TA) is performing context and topic dependent by the combination of research with the scope of advising decision makers. It claims to give contextually-influenced and practical information about the consequences of technology, to assist society in the evaluation of this information, to provide a base for communication about technology and strategies for technology implementation [120]. TA literature often points out that this "shaping" of technology is achieved not merely at an engineering level but also on a level of shaping societal framework conditions [18].

Constructive Technology Assessment (CTA) has in relation to other TA streams a strong technology orientation. It was developed as an academic-theoretical line within transdisciplinary research [17] in the Netherlands by [18] and was adapted in several countries [120]. It is understood as a soft intervention strategy in the development of technology to minimize mismatches, social conflicts and wrong investments in the face of the lack of knowledge of the social embedment of technology. CTA is interested in the dynamics of the process of technology development and implementation, where impacts are being built up, and co-produced, during the process of technical change. Technology impacts on its environment are not seen as passive effects but actively sought or avoided by technology users and producers, and other actors such as governments or pressure groups (NGO´s) which have all their own concrete goals, interests and values. The inclusion and modulation of different stakeholders and alignment of different visions and expectations [18], [121] is the core of CTA. Such modulation activities remain an empty phrase without a defined meta-level criterion for a desirable development goal [18]. Creating "*better technology in a better society*" and sustainability are often named as unprecise meta-goals in CTA literature [18], [120].

This section gives a brief introduction to the background of CTA by giving insights into co-evolution of technology and society, multi-actor dynamics as well as the desirable goal of "sustainable development." Finally, CTA is presented in detail as a guiding framework for this research.

3.1 Socio-technical dynamics: A brief overview

Technology itself is seen as a part of a seamless web of highly related heterogenic elements as organizations (manufacturers, research, and development, end users, etc.), resources, scientific elements and legislation (law). Societal functions such as transport and energy supply are results of such clusters of heterogenic elements which can be named *socio-technical systems* [122]. Technology is always embedded in sub-systems (e.g., a company, academia etc.) of such complex socio-technical systems. Views about the meaning and value of technology are also rooted in these sub-regimes. The development, production, use, profitability, environmental impact, user acceptance and disposal of technology artifacts in combination with organizational and legislative artifacts entail the development of a sub-system and the entire socio-technical system [8] [123].

Technology is composed of materials and components that are combined into a working system. A precondition for the latter are configurations that work including the skills required to install, operate and manage technology (e.g., infrastructures, labor and cultural norms including selectors). The concentric system view based on [124] underpins this as depicted in Figure 3-1. In the center of this view is the hardware (technological artifact), followed by the software (developers, skills, and knowledge to operate technology, e.g. system integrators) and orgware (infrastructure, a division of labor and cultural norms, e.g. utilities, politics). The outer concentric ring, the socioware includes the embedment of technology (the conjunction of society itself) in a particular societal context [121] and [124]. The orgware and software are seen as an integral part of technology within the concept of socio-technical systems. All these factors are highly dependent on each other through social linkages as well as developments within the socioware.

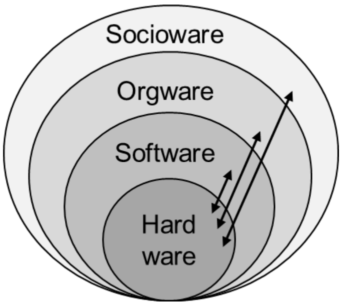

Figure 3-1: Concentric systems view where hardware represents a specific technology, software the ability to operate it, orgware the infrastructure and cultural norms to manage technology. The socioware refers to the societal embedding of technology in a particular concrete societal context [121], [124]

It is possible to link this concentric perspective to different sociotechnical regime dimensions identified by [125] within the multi-level perspective (MLP) framework [5]. This perspective distinguishes three levels of heuristic, namely: Sociotechnical landscape, socio-technical regimes and niche innovations which are linked to the concentric view. The socio-technical regimes refer to shared routines in a certain community including scientists, users, and special interest groups which directly or indirectly contribute to the patterning of technological development [28]. They may represent the software and orgware in a concentric view. The socio-technical landscape refers to an exogenous environment that is not directly influenced by niche and regime actors and can be seen as the socioware out of a concentric perspective. Examples for this are macro-economics and –political developments, or changes in deep cultural patterns. The Energiewende might be seen as such a development. Changes on this level occur of a long time, usually decades [28] [28]. Niches are considered as incubation rooms protecting novelties against dominant market selection (support schemes for renewables as wind or PV). Small networks of specific actors are for example the promoters of niche innovations [28] (small companies, developers). The relationship of this three levels is considered as a nested hierarchy, where regimes are embedded within landscapes and niches within regimes [126]. The kernel of the concept is that innovations can diffuse through the interplay within the dynamics between the three levels [126].

3.2 Emerging irreversibility and entrenchment

The properties of emerging technology entering into a socio-technical system are not given beforehand, but they co-evolve with interactions which occur during development, implementation, adoption and broader use of it [18]. This process is referred as “*co-evolutionary process”* and begins with an innovative product against an existing societal-technical regime which sets up the rules. This process is characterized by the involvement of multiple actors situated in different sub-regimes and takes place at different aggregation levels. It is important to recognize that from this process multiple different views on technology development might arise that cannot always be reconciled entirely with each other [7].

In case of a more significant technological transition as the Energiewende, a replacement or reconfiguration of embedded socio-technical practices and regimes might occur and offer opportunities for new technologies by creating new standards or dominant designs, reconfiguration of the system, changing regulations, infrastructure and user patterns [5]. In such a situation emerging irreversibilities can arise which are reinforced when actors start to invest in technological paths that seem to emerge [20] [127], e.g. through collective roadmaps representing articulated expectations which paths a collective of companies or an entire industry should follow[20] [127]. Such irreversibility's can facilitate certain technological paths but make it also more difficult to make something else. Such potential constraining actions and views can span up "endogenous futures". There is the danger that such expressed development targets may distract us from potential solutions by taking us into the wrong direction. Such processes are not deterministic, actors can anticipate them and create "better" paths [20]. From this arises a phenomenon cited as Collingridge dilemma [12] which states that: in early technology development stages opportunities to steer are plentiful, but hard to choose from, while at later stages this is reversed [13] [12].

Typical questions in this context are questions of how to steer the development of emerging technology and its societal context before technology entrenchment limits the potential for intervention. Such entrenchment appears gradually over time through the aggregation of irreversibility's linked to a technologies conception, to diffusion into and success in the market. Decisions and actions leading to entrenchment are framed by visions and expectations as they express the ideas and intentions about how the future will be [121][21]. Notions about what technology could be is a natural in every emerging technological field and has to be seen in contrast to already proven innovations and applications in case of established technologies. Positionings of actors as well as their relations are often unclear and remain in-transparent in this phase, resulting in a high uncertainty about future paths. It is not clear what actors are doing and should do to make technology successful [128]. The power of such expectations and visions about technology depends on the degree to which actors share them among the system. This degree of 'sharedness' ensures that stakeholders act accordingly to these expectations. Expectations can thus inspire development and the related trajectory of new technological developments that subsequently have to be protected by other collective expectations [121].

3.3 Sustainable or "better" technology as a meta-goal for CTA

Sustainability potentials are often named as a major goal in literature or policy documents when it comes to the selection or development of technology. The concept of sustainable development (orientation towards efficiency gains and improvements of technology) and sustainability (perspective on related to individual values and attitudes towards nature) has been object of interest in a wide spread of literature and other diverse discussions as in [123], [9], [129], [130] and [7]. Sustainability of technology is also often mentioned as a goal in CTA literature in line with wealth creation, safety, and quality of life [18]. All these factors can be seen as rather redundant mentions and are simply summarized as *"better" technology for a "better" society*" in CTA [120]. There is no definite formulation provided of what "better"

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[20] E.g. through technology lock-in, sunk costs, economies of scale, technological interrelatedness etc.
[21] This represents a well-known phenomenon in social sciences referred as Thomas theorem [121]

means but it can be assumed that CTA-authors implicitly refer to more sustainable technology. It is thus worth to take a closer look at sustainable development and the resulting implications of what "better" technology might potentially refer.

The concept of sustainability itself was first formulated in the Brundtland Report "*Our common future*" from 1987 [131] and defines sustainable development as follows:

> *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."*

This definition inhibits on the one side aspirations between humanity towards a better life and the limitations imposed by the state of technology and social organization on the ability of nature to meet this needs on the other side [132]. Environmental concerns are essential for this view on sustainable development, but the primary argument is on welfare in the context of inter-generational equity. There is no intrinsic value to care about the environment but to preserve resources for our children [132]. This makes sustainable development synonymous with growth, where it means ameliorating but not challenging economic growth and existing political order [7]. Sustainable development represents a particular shift in perspectives, away from a focus on purely economic development towards a more multidimensional development[22] or something as a "better society". These dimensions have been re-interpreted to as encompassing three pillars namely; environmental, social and economic factors [123]. The relevance of those dimensions is extensively discussed in the literature, e.g. [1][23] [133][24] and [134][25]. These dimensions can be seen as highly opposing imperatives of growth and development on the one side and the ecological, social or economic pillar of sustainability on the other. Being able to reduce environmental impacts in economic activity does not mean that it improves the quality of life for all. There are differences in the meaning and value of different sustainability dimensions which are rooted in different perceptions. In this sense, sustainable development can to a certain degree be considered as an attempt to square a circle [7].[26]

Sustainability of mankind´s development is highly dependent on socio-technical systems[27] which determine to a large extent the demand for raw material and energy, needs for transport and infrastructure, emissions, mass flows of materials and composition of waste [120], [135]. Technology serves as a key factor in the innovation system influencing a multitude of dimensions as prosperity, lifestyles, social relations, and cultural developments. Thus, actions taken in the development, production, and disposal of technological products and systems have a high influence on the environmental, societal and economic dimension of sustainable development or maybe the "*embedment of better technology in a better society*". Related assessments should therefore always entail the entire life cycle of a product.

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[22] There are other preferences as a more dualistic topology that focuses on the relationship between humanity and nature [7]

[23] Refers to the integrative sustainability concept developed at Institute of Technology Assessment and System Analyses.

[24] Supposes to reject the idea of pillars and formulated principles on which sustainability could be based on.

[25] They distinct five paradigms for environmental management and propose a set of multiple factors to be included.

[26] Which is impossible.

[27] It should be noted that sustainable development should also be discussed on base of radical shifts in individual behaviour, politics or other radical social arguments that tackle current neoliberal economic orders and proposes an alternative system [7]

There is no definitive formulation of sustainable development or “better technology”, it remains contradictory, inhibits complex interdependencies and creates other problems. Sustainability-related problems are constantly changing as they represent the continuous negotiation of preferred futures under deep uncertainty. It is a normative concept nested in real-world problems and dependent on different sets of individual values and moral judgments [7]. There is no final sustainable state, nor a fixed condition or common definition available for the concept of sustainable development. It is rather seen as an inherently dynamic learning process [123]. There is also no conclusively “best” technology solution to achieve something as infinite sustainability or a “best” technology [123].

Technology itself is not sustainable, but it may contribute to sustainability depending on the social dynamics in the context [120] (its socio-technical embedment). It causes several problems emissions and costs but is also considered as a solution or at least as one aspect of the solution of societal problems [9]. The stamping of this contribution remains fuzzy; it is unclear if or when it will appear as well as how it will look. These aspects make it challenging to determine which factors and methods should be integrated and applied when it comes to a sustainability assessment of emerging technology. Additionally, it is claimed that such assessments shall be considered in practical decision making [136]. This has fostered several conceptual, theoretical and methodological developments and their constant refinement in the field of sustainability [7].

3.4 Modulation of socio-technical developments in the face of “sustainability”

The concept of socio-technical co-evolution implies that the socio-technical embedment of technology is the core for sustainable development [137]. Again, the interplay of different spheres of a socio-technical system related to “sustainable” or “better” technology development can be – in a simplified way - broken down into different rings. Each of these rings represent a certain sub-regime within a concentric view as depicted in Figure 3-2 (rings can of course vary and are not comprehensive). There is no direct deterministic relation between technology and a certain socio-technical sub-system to achieve a more sustainable development [123]. It is rather a more complex process, where they influence each other iteratively and mutually via a high magnitude of different aspects [123].

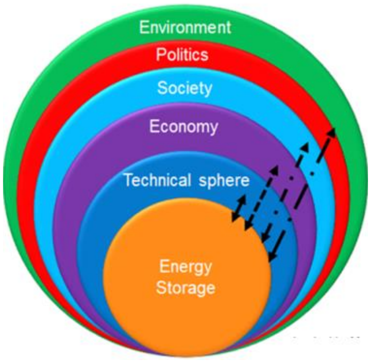

Figure 3-2: Sustainability perspective on electrochemical storage systems (based on [123] and [14])

This process is nested in different socio-technical regimes which include multiple stakeholders and has a highly experiential as well as experimental character. The concept of sustainable development has thus not only to integrate different sustainability dimensions but also has to be extended across sectors and interests by recognizing multi-actor dynamics and differences. A design and decision dilemma arising from the claim to achieve better technology is to find the right “shape target” (e.g., environmental vs. economic vs. social aspects) before entrenchment limits potentials to steer technology development. As explained before, actions and interactions that shape technology in regard of sustainable development are based on two elements, namely expectations and visions, this comes especially true in the case of emerging technologies [7].

They are crucial elements to achieve desired futures as they can set technology on a particular trajectory and determine the outcome of technological change and (non-) sustainable development [121]. This results in ambiguity to achieve sustainable development as follows

A) There is a strong need to prospectively identify, exploit and exhaust possibilities to shape or select emerging technology alternatives based on visions and expectations according to different sustainability dimensions.
B) Potential trajectories of technology have to be unveiled based on actors visions and expectations about the use and development of technology, its specifications and market use that determine sustainability.

To modulate technological innovations in a more sustainable or “better” way makes it necessary to understand the primary target group of actors which works with technology and that they work within concentric perspectives [138]. The work of [139] distinguishes two levels of actors when it comes to expectations socio-technical developments which can also be applied for sustainable development; so called insiders and outsiders [138]. Both groups have different social construction processes that impact the way of how they assess technology and perceive sustainable development.

Insiders are actors directly associated with technology which are often not informed or not knowledgeable about development and issues at stake for different professional environments (e.g., business, end-user, government) [128] and are strongly technology focused. They are referred as “*Enactors*” which try to realize new technology and identify with it and tend to emphasize positive aspects (e.g., think and work in “*enactment cycles*”) [20]. The opposition may be disqualified as irrational or misguided or following own agendas. Enactors identify themselves with a technological alternative and perceive the world as waiting for their product [20], and the enactment frame leads them to a concentric notion of “*making the product right, then look at the market and regulation and then afterward worry about public acceptability*” [140].

Outsiders also referred as “selectors” are non-technology development related actors which get somehow directly or indirectly in contact with the final product (governments, regulation, NGOs, end-users). These actors usually observe technologies from the outside and compare them with other parallel developments. The specific properties of a technology play only a small role for most of this kind of stakeholders (so-called black box effect) when it comes to “pick” the “best” technology. Comparative indicators for technology selection as costs, applicability, environmental impacts, and safety are more relevant for them [141] [20].

Responsibility is distributed over selectors as well as enactors when it comes to “manage” technology in society with the goal of sustainable development. The nature of responsibility though is different for each kind of actors. At the end, all kind of actors are required and have to interact to create better technology [18]. A precondition for the modulation of sociotechnical developments is the provision of spaces for interaction, exchange of visions and expectations.

3.5 Constructive Technology Assessment as a soft intervention strategy

The previous chapters provide the theoretical background for CTA regarding the normative meta-goal "*to create better technology in a better society*" which is seen as closely to "sustainable development." The following section provides a summary of the theory and a more detailed view on the aims, strategies and typical process steps of CTA named in the previous sections.

Main theoretical aspects relevant for CTA are namely co-evolution of technology and society, entrenchment, emerging irreversibilities, positioning, spaces, multi-actor dynamics and endogenous futures [142] which are summarized in Table 3-1 for a better understanding of the approach.

Table 3-1: Summary of grounding concepts of CTA based on [121], [127] and [128]

Concepts	Summary
Entrenchment	• Technology becomes gradually more entrenched and is steered by the actions of actors involved that take development into a specific direction • Is a concept of social sciences of innovation also referred as path dependency in economic theory • The level of entrenchment results from the accumulation of irreversibilities
Emerging irreversibility	• Refers to patterns that enable certain actions and interactions, while constraining others e.g. all resources are limited, if they are allocated to a project, another will have to do without them • An indicator for irreversibilities are stakeholder's expectations involved in the agenda building that follows from expectations.
Expectations of emerging technologies	• Decisions and actions are framed by intentions and ideas about a future situation • Taking expectations as facts reduces the subjective degree of uncertainty • The power of expectation lies in the "sharedness" of them among the system • They can inspire new technological developments
Positionings	• Refers to the allocation of roles in line with positioning theory in social psychology • It states that no stable roles have been established, they are rather continuously shaped and altered based on expectations of actors of how they see their role and the role of others
Spaces	• Channels of communication of expectations between stakeholders and the way they are organized (anything that provides opportunity for interaction) • There is often an absence of channels when it comes to emerging technology
Multi-actor dynamics	• The concept defines two categories of actors involved in technological development namely; Enactors – technology actors, e.g. developers that are rallied behind a certain technology; Selectors – societal actors who take a position of comparing and selecting technology, e.g. users or governmental groups with a more distant relation to technology

CTA has the aim to broaden and positively influence technology development processes by addressing potential innovation obstacles or impacts as early as possible [141], rather than assessing ex-post the impacts of more-or-less finalized products [130]. There is no "perfect timing" to start such a process; it should take place before the level of technology entrenchment is too high making it too difficult to conduct desired changes as these might be too expensive (the technology has probably already achieved a certain market diffusion).

CTA is a strategy to achieve goals of wealth creation, safety, and quality of life and to conduct actions to promote technologies that promise to have mainly such desirable impacts and few undesirable impacts [18]. Doing so CTA can be interpreted as a pragmatic view which has an interest not only for what “is,” but also what might “be” caused by actions in technology development. It owns a role of an intermediary and offers a way to change actual situation. Action must be guided by purpose and knowledge as well as awareness of epistemic limits in order to perform changes in the desired way [143] [144]. From this results the view that the world is changed through reason and action and the acknowledgment that there is an inseparable link between human knowing and human action [145]. Doing so, it recognizes that the world is in the state of continuous becoming and is concerned about action and change as well as the interplay between knowledge and action [144]. There is the (maybe moral) need to present knowledge that has consequences for future applications, to unveil what differences this knowledge will have in practice and how it preferably leads to improvements. Moreover, a belief that knowledge has to be generated and disseminated among and through relevant actors.

Having this is mind CTA as a transdisciplinary research framework represents a soft intervention by confronting *enactors* with the visions, interests, and expectations of *comparative selectors,* and vice versa to create new knowledge of how to reach desired goals. There is no canon of “CTA methods” available that can be used for every case. Several methods in design practices can be included within CTA that anticipate impacts, involving actors and allow any kind of social learning [18], [121]. This justifies a widespread application of new methods, strategies, procedures and design solutions that can contribute to develop or exploit technology beyond common/traditional applications. There are, however, at least three general and generic intervention strategies identified by [18] which should be considered in every CTA based approach:

- *“Technology forcing: Inverse Anticipation and Feedback”:* – technology forcing by regulation from authorities (government agencies, insurance companies or banks, etc.) in which desired impacts are stipulated, and technology actors have to fulfill these (e.g., emission restrictions). The strategy takes place over societal actors
- *“Strategic Niche Management: Graded learning and Feedback”:* - introduction of protected niches for technology development in which different actors (mainly enactors) learn about user needs, design and political acceptability. The strategy takes place over the technology actor
- *“Alignment: Loci for Reflexivity and Feedback”:* - aims to create and exploit loci (real spaces, forums, institutionalized linkages between supply and demand) to offer possibilities to modulate development. The strategy includes the societal as well as technology side

It is recommended that the three presented strategies should be mixed regarding particular cases in order to stimulate anticipation (*identify effects or impacts of new technologies […] co-produced during the process of technical change*), learning *(“[…] to explore possible new linkages between a range of aspects, e.g. design options, user demands […]”*) and reflexivity *(“[…] avoid falling into contrast between technology and society […] to recognize different roles of stakeholders in different regimes*”) [18].

CTA can create and orchestrate spaces in which interaction can occur, e.g. through workshops, interviews or surveys even if interactions between participants might be partial. Such interactions are mainly supported by socio-technical scenarios to show effects of interfering enactment and selection cycles and are told to give a solid base for the interactions [20]. The idea is of this intervention is to enable actors to do better in their environment by contributing to more desirable paths [128] such as sustainable development might represent. Figure 3-3 provides an overview of the role of CTA by providing a space for enactor-selector interference to break through typical enactment cycles by shifting the locus of assessment towards a broader perspective. Following [128] CTA can (but does not have to) be divided into three general phases which are as follows:

1) Providing in-depth information about the topic in line to a) decrease asymmetry that is inherent in any emerging field; b) provide information yet not available but needed for participants to develop visions and build arguments on [128].
2) The CTA analyst stimulates participants to articulate their prospective view to eliciting personal expectations and visions of the field. Such inquiries have to carried out carefully and individually, e.g. by face to face interviews [128]
3) Finally, a platform for interaction, e.g. through a dialogue workshop is provided where participants discuss presented scenarios and brainstorm to formulate technology options, which are combinations of applications for specific markets or practices as well as potential impacts of these. The ultimate goal of such an event is to achieve convergence which can be tested, e.g. by a prioritization matrix to unveil which applications and technology properties are seen as most feasible by workshop participants. There is no guarantee that convergence will be reached [128] but participants become at least aware that there are different perspectives which they can take into account for their further actions [128].

CTA practitioners mostly use qualitative narrative methods expressed through prospective socio-technical scenarios developed in face to face interviews and derived from stakeholders thoughts [146], [20], [147]. Practitioners than interpret meanings about the world of actors they got in touch with and then try to transfer this knowledge into probabilities of how technology may be embedded in society. This interpretation in the form of socio-technical scenarios is used as a narrative for an interaction base for stakeholders, preferably through a workshop, to discuss and brainstorm of “how to achieve better technology in a better society.” There are critics who state that using socio-technical scenarios including their interpretation might be very blurry and that the use of CTA is thus restricted to an exclusive idealistic forum following an esoteric agenda [13]. However, new methods can be tailored to every CTA project [121].

It is necessary to see if the goals of CTA are achieved if actors are chosen and assigned correctly, if there was achieved a sufficient support to participate in discussions and if the set-up allowed represent a sufficient interface between enactors and selectors. Follow-up interviews after a workshop are a measure to validate if the CTA exercise was successful. And, if actors have developed a shared frame of applications [128]. Such interviews can be conducted via telephone within a frame of up to 10 months after a workshop [146].

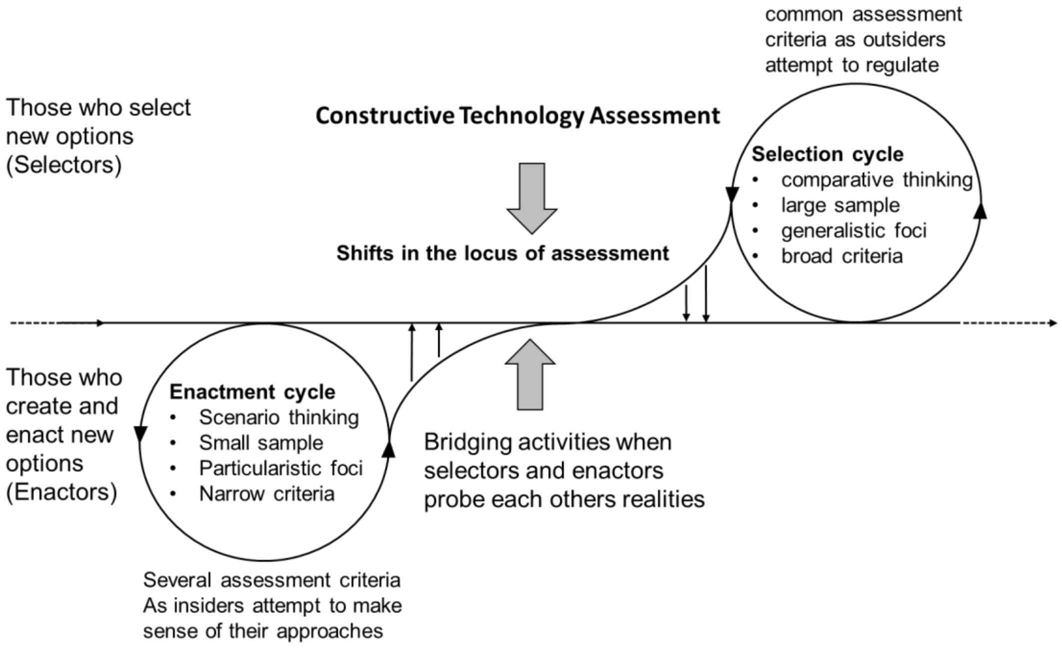

Figure 3-3: Scheme of dynamics in the constitution of a technological field (based on [139])

4 Methodology

The following chapter provides an overview of the methods used to answer the research question stated in the introduction. It must be mentioned that the explorative work of Versteeg et al. [121] and [148] has provided valuable input for the conceptual set-up of this research. First, the scope of the research is specified, and sub-questions are formulated based on previous chapters. Then used methods are introduced in the next sections. Finally, the analytical framework is explained.

4.1 Scope of the research

The work on hand represents a transdisciplinary research carried out under the frame of Constructive Technology Assessment (CTA) principles with an orientation towards *Alignment: Loci for Reflexivity and Feedback".* The research can be expected as an experimental attempt to a) explore actor visions and expectations about battery storage properties and its application and b) to use this information to provide detailed information about the consequences of the first through quantitative modeling.

A high emphasis is put on displaying quantitatively the consequences of normative expectations on "better" battery technology design which is seen as a novelty in comparison to popular set-ups for CTA (qualitative formulation of socio-technical scenarios as a base for discussion). Creating "better" technology is used as a loose term in CTA literature which can be understood as synonymous with creating more sustainable technology. This work does not claim to provide a full sustainability analysis or LCSA, including all the discussions that emerge around the topic of sustainability. Instead, it refers to the term of "better" technology used in CTA with an orientation towards named sustainability dimensions and criteria in the literature (see chapter 3.3 and 3.4).

A broad master narrative related to the domain is derived to avoid a too narrow view (or enacting view) on battery storage. The usually last step of CTA, the provision of a platform for interaction of actors to achieve alignment of visions, e.g. through a dialogue workshop is too large for this project. Nevertheless, the work aims to identify quantitatively the degree of "consensus" among actors to provide a potential base for a focused discussion and alignment within such a platform. At the end enabling social learning is the core of CTA, results are thus distributed across participants who are interested in feedback. A gap which cannot be filled by this work is to prove if something as social learning is achieved through this new combination of methods.

The study mainly uses generic data and is carried out in detail for stationary battery systems. It does not allow assessing the merit of innovation of properties that are not available in today´s technology portfolio. Modelling is based on today´s commercial potential for energy storage within the European electricity market. The exchange between different sectors as transport is possible but not considered here. There is a high magnitude of available battery storage technologies, and it is not possible to include all of them, this also comes true for other flexibility options. The battery technologies analyzed here include a comparison of All-vanadium Redox-Flow batteries (VRFB), Sodium-Nickel-Chloride battery (NaNiCl), valve-regulated Lead-Acid, Lithium-Iron-Phosphate battery (LFP) and Lithium-Titan-dioxide (LTO), Lithium-nickel-manganese (NMC) and Lithium-nickel-cobalt-aluminium-oxide batteries (NCA). For a more systemic perspective, a selection of these technologies is compared to established conventional technologies namely pumped hydro storage (PHS) and a diabatic compressed air energy storage (CAES) in a long-term storage application scenario. Hydrogen, power to gas, double use of electric vehicles (V2G), second life cycle traction batteries and demand-side management are not explicitly considered in this work.

4.2 Specification of research questions

The development of electrochemical energy storage technologies can be understood as a process of social learning where questions arise about the technical optimization of single components and the specific implementation (use) of the technology. This process is linked with political and societal aspects relevant for a high number of actors [146]. The research question stated at the beginning is:

> **What is the future role of different stationary battery storage technologies within the German energy turn-over and what expectations do actors have regarding their characteristics?**

A conceptual decision flow diagram (Figure 4-1) helps to contextualize related questions which a decision maker might have considering a) choosing battery storage as a balancing option in general b) the choice of the right battery technology for a specific application area considering actor expectations. It is an example for an iterative decision process inspired by [149] to illustrate the potential logic of a decision in the context of the proposed research framework.

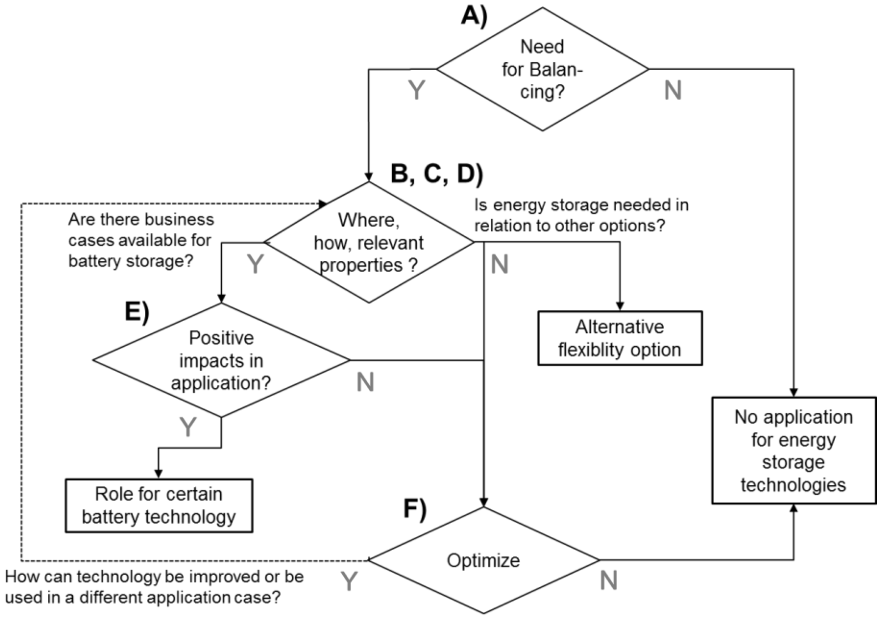

Figure 4-1: Schematic decision process for the implementation of energy storage out of a sustainable development perspective linked to the research questions A-F (own draft inspired by [149])

The hypothetical decision process for this example firstly starts with the question if there is a need for balancing within the future German energy system. If there is none, there is no need to proceed, and no batteries are required in an oversimplified way. The requirement for balancing technologies can then be associated to the question if there is a suitable business case available for battery energy storage and if they can compete (if there is any competition) with other flexibility options.

In case of an absence of viable business cases for battery storage, other alternatives are chosen. If there is a potential application available one has to decide which battery technology to choose. Different technologies must then be tested, evaluated and compared to each other according to expectations related to their properties. In case of low performance of specific technology an alternative should be taken and vice versa in case of a good performance. If a certain technology scores low strategies of shaping technology or using it in a different application field might lead to alterations and a positive decision within a further iterative loop (not covered in this work). This decision process can be broken down into four theme blocks and eight concrete sub-questions as follows which are also indicated in Figure 4-2:

1) Questions related to the general role of battery storage as a flexibility option:
    A) Is there a need for battery energy storage in respect of other flexibility options and what are the main driving forces and obstacles for it?
2) Questions specifically related to battery storage
    B) Identify new linkages between a range of aspects, e.g. design options, user demands, business models and potential system integration levels of battery storage
    C) What demands and expectations do different actors have regarding key parameters for battery systems for a “better” (sustainable) embedment of technology into society?
    D) Are there shared expectations among actors on energy storage properties and use for energy storage among different actors?
3) Question about impact of expectations through technology evaluation
    E) What are the effects or impacts of different energy storage technologies in selected application scenarios regarding identified criteria and use cases?
    F) Which technologies perform the best based on C, D, and E?
4) Questions about future research points (thus not included in Figure 4-1):
    G) How can results be used to inform actors and to achieve something as “better technology”?
    H) How can this process be opened for future assessments to provide a broader basis for decision making and technology design?

The perspective of CTA offers three significant analytical achievements relevant to answer the given questions: socio-technical mapping, early and controlled experimentation enabling to identify unanticipated impacts and the creation of a dialogue between insiders and outsiders [150].

4.3 Applied methods

A set of quantitative and qualitative methods can be tailored and combined for a CTA project. As discussed in the chapters before the core of CTA is that chosen methods should stimulate A) learning to explore new aspects e.g. design options and user demands; B) reflexivity to recognize different roles of stakeholders in different regimes and C) anticipation to identify effects or impacts of new technologies co-produced during the process of technical change [18]. The triangulation of methods and sources, as well as closeness to empirical phenomena, is seen as a way to achieve the three forms of stimulation [145].

As in most research projects, a literature review is conducted which is then followed by a stakeholder-based inquiry. The research question is formulated broadly at the beginning with the ulterior goal to maintain a holistic view of major implications of the domain and to reach a broader population of researchers and actors from the application side/selectors. After this, questions are explicitly centered on battery storage technologies properties and their use and are more oriented towards enactors. A preliminary inquiry is conducted with informal talks, followed by an online test survey with feedback comments and semi-structured interviews of both actor groups. The use of different data sources (literature, preliminary survey, and interviews) is used to stepwise structure the survey and the multi-criteria decision model (MCDA) (contribution to A – learning) and consequently, define scenarios for technology evaluation through a set of system analysis methods. Triangulation of methods can help to gather a deeper understanding of different actor visions and expectations in an interpretative (semi-structured interviews), and their validation is an empiric way (survey). Beyond these two classical forms of inquiry, MCDA can be seen as a valuable method to obtain different normative expectations by attributing weights to different aspects of sustainability (contribution to B – reflexivity). These expectations and visions must be transferable to “the real world” and must overpass conceptual discussions otherwise there is a danger that discussion results may collapse to insignificance the moment you force them to test and to trace real consequences [143]. Based on criteria defined in MCDA and corresponding weights, the anticipation of effects is analyzed through a set of system analysis methods as life cycle assessment and costing (contribution to c – anticipation). All steps of the research are given in Figure 4-2 which also refers to the single chapters.

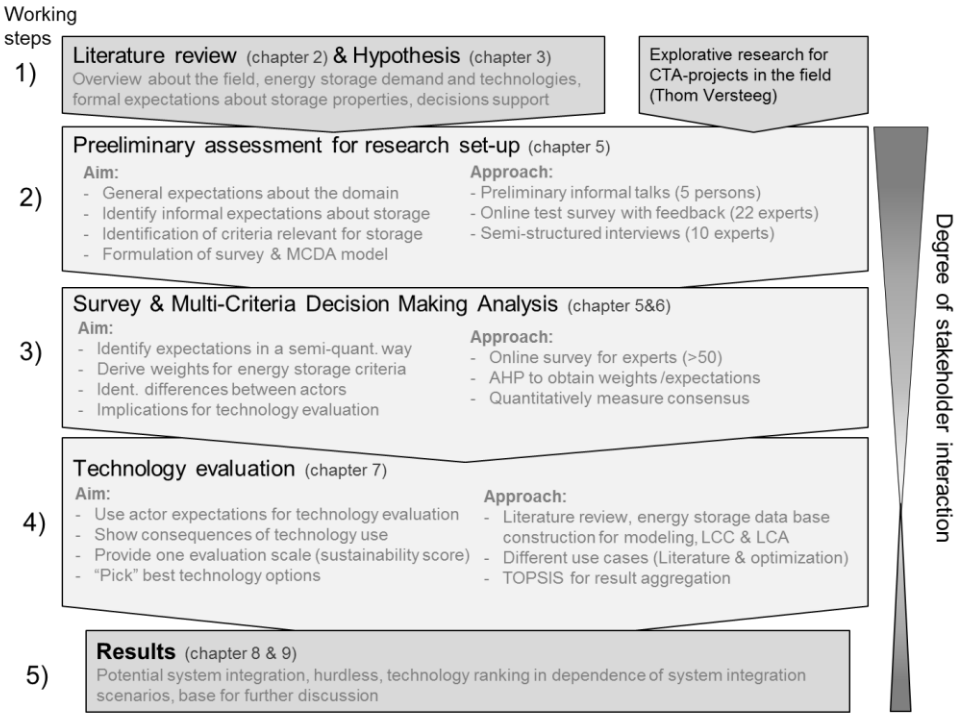

Figure 4-2: Resulting research design for prospective system analysis following meta-heuristics of CTA

The degree of stakeholder interaction is the highest in step 2 and 3, step 4 - the phase of modeling includes only an indirect interaction of stakeholders but builds up on some of the questions raised in the preliminary assessment. This point is specified at the end of chapter 5. Step 5 – the presentation of results includes the distribution of results among stakeholders.

4.3.1 Stakeholder engagement

The following sections discuss methodological issues related to the involvement of stakeholders. Three approaches are applied to inquire actor expectations and visions of energy storage and sustainability. Firstly, explorative semi-structured interviews are introduced together with the conducted survey. Finally, MCDA is briefly presented as method beyond typical forms of inquiries within CTA. More information about the single steps is given in the corresponding chapters.

4.3.1.1 Survey set-up and semi-structured interviews

The survey served as a base for semi-structured interviews and was continuously enhanced during a pretest phase that consisted 3 phases. The first phase consisted of informal discussions at the candidate's home institutions to structure the survey. These first versions were sent to a selected set of external experts able to comment the survey in the sense of critical reviewers. Beside technology system integration and application issues, a first set of relevant criteria was included here. Actors where then interviewed based on the questions and proposed MCDA criteria of the survey.

There are three general forms of interviews: structured, semi-structured and unstructured interviews. Structured interviews are eligible for descriptive research, whereas unstructured ones are used for exploratory research. Semi-structured interviews offer a way to combine exploratory and explanatory insights [149]. The motivation to conduct interviews in this research was to obtain particular insights into the problems that different actors face nowadays and to find out what expectations and visions they have for the future use on stationary energy storage systems. Semi-structured interviews are explored to provide sufficient structure as well as flexibility to tackle this task. All interviews had a length of 20 to 120 minutes.

After this pre-test phase, a consolidated version of the survey including an MCDA model was spread among relevant stakeholders for reasons of empiricism and to gather preferences regarding the shape targets of stationary battery storage in respect of sustainable development.

4.3.1.2 Multi-criteria-decision-analysis

Multi-Criteria Decision Analysis models (MCDA) can be seen as a valuable method to obtain normative knowledge about of "*about how the world should be*." The uncertainty inhibited in this assessment is based on the fact that shape targets for an optimum technology construct are dependent on multiple actors preferences which by contrast to physical / tangible factors represent a psychological realm claimed to be intangible as they are related to subjective ideas based on beliefs of the individual about himself or herself and the world of their experience [151]. This complexity and inherent uncertainty of early-stage system analysis are re-enforced by the unclear (or yet not existing) socio-technical embedment of emerging technology. This situation makes it difficult to disaggregate or allocate technological, societal, environmental and economic impacts. MCDA as a sub-discipline of operations research explicitly consider such complex decision problems and provide a possibility to tackle them [101]. Especially the Analytic Hierarchy Process (AHP) developed by [152] in combination with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [153] is identified to be an adequate method in the frame of this research.

It is important to mention that MCDA is not able to identify the ultimate right solution, as there is never a perfect solution available in real life [154] as pointed out by Phillips as follows [101]:

> *"…. decision theory has now evolved from a somewhat abstract mathematical discipline which when applied was used to help individual decision-makers arrive at optimal decisions, to a framework for thinking that enables different perspectives on a problem to be brought together with the result that new intuitions and higher-level perspectives are generated."*

MCDA is considered as a support for decision making with the aim to support decision makers to organize available information, to rethink consequences of alternatives and to explore their own perceptions and needs [155]. Further decisions and preferences are expressed in the form of equations, inputs, and coefficients which can be observed and reproduced by other specialists [156]. In this way, MCDA provides essential, reproducible as well as objective insights and allows to grasp strategic intelligence about influence parameters of new technologies and their sustainability which at the end result from their socio-technical embedment.

The degree of "sharedness" of visions and expectations about technology design is seen as a base to identify discussion points to achieve alignment among actors. The use of methods as the Shannon entropy or beta- and gamma diversity offer a solution to make this visible based on AHP results.

4.3.2 Technology evaluation through system analysis

The need for system analysis emerged from the increasing complexity of modern technology. It is a collective term for mostly quantitative but also qualitative methods which are used for technology planning, development, decision making and broad assessment also from non-technical criteria [157]. System analysis aims to reproduce certain phenomena (e.g., the energy system, electric vehicle, specific component) including their properties. This is done via formal approaches to reduce the complexity of a (technical) system and its surroundings by problem decomposition into sub-problems. And, enables it to trace real consequences of "actions" taken in technology development.

The major step within almost all system analysis approaches is the definition of a system and its borders. A system is always in interrelation with its environment (may it be markets, nature, an electric engine or society). Over its borders, there is a continuous flow of in and outputs as depicted in a schematic way for a technological system and a market in Figure 4-3. This approach makes it possible to understand major dynamics inhibited in such a system and to identify "screws" that might lead to a better system.

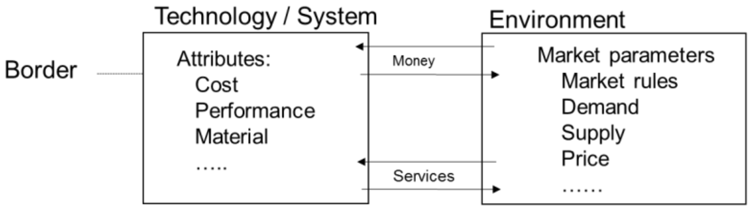

Figure 4-3: Scheme for the interrelation of a technological system showing the exchange of services and money with its environment [149]

Some typical quantitative and qualitative tools used for system analysis tools are techno-economic assessments, economic-, social- and ecological life cycle assessment, material flow analyses, ABC-Analysis, and energy system modeling, etc. [157], [142]. The choice of the right system analysis tool depends on the specific research question, technology as well of its development status. In case of the assessment of emerging technologies the more distinct term "*prospective system analysis*" (PSA) is sometimes used [19]. This term implicitly inhibits one of the guiding principle of CTA by using quantitative methods to look at drivers, effects or economic, social and environmental impacts of emerging technologies as early as possible in order to avoid unintended effects or at least rise attention to them [158], [19]. Anticipating efficiently potential impacts of emerging technologies before they enter market requires an assessment that covers the entire life cycle of a product or system. This entails production patterns, political as well as economic framework conditions, future developments and markets and usage of technologies [120].

Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (sLCA)[28] are methods that enable the identification and quantification of potential benefits (or disadvantages) of new technology in comparison to other traditional alternatives. These approaches include the extraction of raw materials, production, use phase as well as the disposal or recycling of products (cradle to grave). This assessment is done by accounting for burden shifting between these life cycle phases and the tracking of impacts in diverse impact categories. The different approaches, which are mainly used in this work can be briefly introduced as follows:

- LCA is a "classic" within analytic tools and is an established and integral part of environmental management tools. It is a standardized approach within DIN ISO 14040 [159] and 14044 [160] that documents a product's or product system's environmental impact over the complete life cycle. Such impact categories can range from climate change to human toxicity, acidification, and ozone depletion. It is characterized by four phases; goal and scope definition, live cycle inventory analysis, life cycle impact assessment and the interpretation of results.
- LCC as a tool for management is used by companies for among other things major investment decision processes, alternative production processes, maintenance and logistic concepts [161] to identify potential cost optimizations during a . There is no standard available for LCC but guidelines as the IEC 60300-3-3 [162] or VDI 2884 [161] for general application by both customers and suppliers of products, explaining the purpose and value of LCC and outlines the general approaches involved.
- Other methods: Literature review of relevant articles to build up database for modeling, monte-Carlo simulation to evaluate aleatoric uncertainties and a sensitivity analysis related to LCC and LCA

Analyzing and comparing traditional against innovative products with each of this approaches makes it possible to give feedback to developers, manufacturers or decision-makers about the specific impact of an innovative product system regarding different spheres of technology properties considering various application cases expressed through numeric values [19]. The named approaches LCA and LCC (as well as s-LCA) can be combined to access technology impacts. There are methods as Life cycle

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[28] The method is not applied in this work as it is considered to be in its infancy as well as the absence of reliable data.

sustainability Assessment available, e.g. [163], [164] that claim to provide a sustainability assessment but which remain at least partially conceptual.

4.4 Analytical framework

The last chapters have introduced the scope, sub-questions and the used methods of this research conducted under the frame of CTA. Stakeholder engagement includes semi-structured interviews, an online survey, and a Multi-Criteria-Decision Analysis model to elicit different expectations and visions about the domain. These expectations are quantitatively evaluated by the use of MCDA and different system analysis methods. None of the presented methods are deemed to be sufficient to analyze the future role of electrochemical storage technologies and their properties. It is postulated that combining insights of all methods under the frame of CTA allows not only gain more profound insights into the economic, environmental and social performance of electrochemical energy storage, but also implications of the larger landscape and niche developments. Combined views from enactors and selectors allow it to shift the loci of assessment to provide a broader picture of the domain. This information is then fed back to interested actors in the form of a short report. Finally, the analytical framework is presented in Figure 4-4. The flow of information indicated in this figure will be explained in the corresponding chapters. Stakeholder engagement is presented in chapter 5 including first results about relevant socio-technical factors and six where MCDA is introduced. Technology evaluation is presented in section 7. Finally results from MCDA and technology evaluation, which are highly interdependent as the first determines what to analyze in the latter are presented in chapter 8.

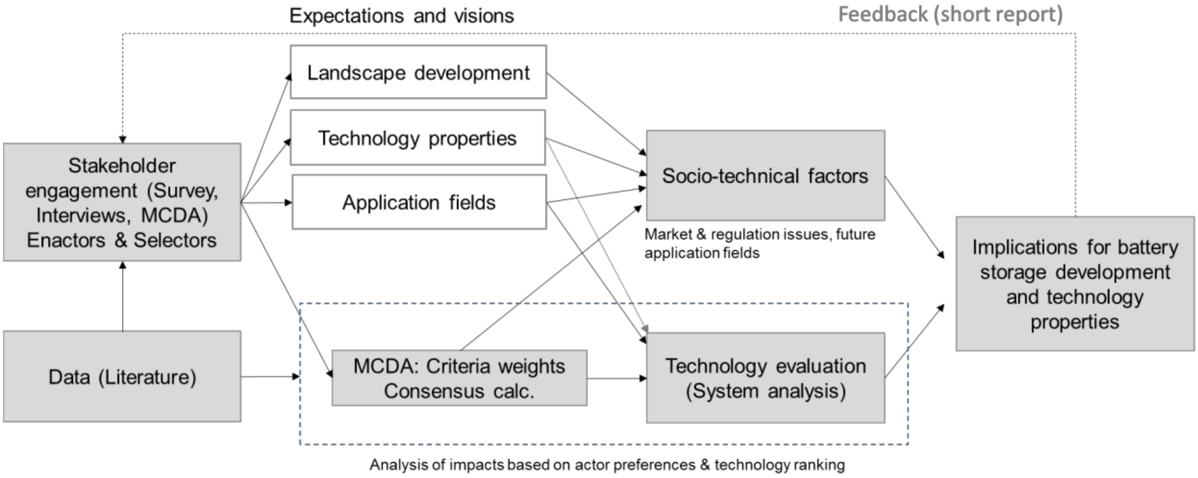

Figure 4-4: Overview about the analytical framework where arrows indicate the flow of information under the frame of CTA

5 Actors views on battery storage as a balancing option

The literature review has shown that there is a high potential for energy storage in the future. This chapter has the aim of exploring the agency of enactors and selectors to identify to what extent other balancing technologies, concerns about technology and market design as well as institutional factors represent a barrier for market diffusion of electrochemical energy storage technologies in the context of the energy transition in Germany. The semi-structured interviews and the survey in this work are structured around the following points:

A) Balancing technologies – questions about relevant developments in the energy system, related expectations on balancing technologies, markets, system architecture and sustainability
B) Grid battery storage – questions about the future use, technical requirements, and application of grid battery storage
C) Desired characteristics of balancing technologies – Analytic Hierarchy Process (AHP) for the ranking of criteria considered as relevant for a better socio-technical embedment (next chapter) and "sharedness" of expectations on these

The interviews are analyzed qualitatively whereas survey results are evaluated statistically by the use of a Mann-Whitney U-test realized in SPSS © to prove if there are significant statistical differences between enactors and selectors. The MCDA approach is explained separately in chapter 6 due to a large extent. The survey and the MCDA inquiry are realized in SoSci Survey © which is freely available for academic research and has proven to be flexible enough for the research on hand. A detailed overview of the entire online survey is given in Annex A.

The first section highlights the process of stakeholder selection and engagement. The following chapter aims to unveil stakeholder visions and expectations about point A. This is followed by more detailed questions about electrochemical storage (point B). Finally, a summary and some implications ofe this further research is presented.

5.1 Set-up for stakeholder involvement and selection

Choice of participants is based on different socio-technical sub-regimes dimensions relevant for energy storage identified by [5] as indicated in Table 5-1. Multiple mentions of stakeholders regarding different dimensions to concentric rings are unavoidable as an explicit allocation is not possible.

Relevant stakeholders of the different named socio-technical sub-dimensions were selected based on three approaches as follows:

1) **Via organizations;** which are known to be a relevant stakeholder were contacted and asked to forward the inquiry to a responsible person for the given topic.
2) **Contacts with relevant skills;** persons with high skills in the field, track record or publications were approached directly.
3) **Snowball principle:** All participants were asked to forward the inquiry to colleagues fulfilling the conditions of the former point

A precondition for actor invitations was to have a balance between all named stakeholder groups of at least 6 participants with a maximum of 50 % of academics [5]. Participants should be experts in their field but not necessarily in the field of stationary battery storage. A primary aim was to contact mainly principal investigators, higher management and project leaders.

Table 5-1: Different socio-technical dimensions and corresponding stakeholder groups within a concentric view of energy storage in general inspired by [5] and [149].

Socio-technical sub-regime	**Stakeholder groups and their location within a concentric system view**		
	Software	**Orgware**	**Socio-ware**
Technology	Developers, academia, manufacturers	Developers, academia, manufacturers, industry	Political goal: transition of the Germany energy system towards an RES share of 100 % in 2050
Industry	Developers, academia, manufacturers	companies, networks operators, developers, RES system integrators, component manufacturers (inverters, etc.), Energy storage industry	
Infrastructure		Transmission & Distribution System operators (TSO &DSO), utilities, academia	
Policy		Regulators, academia, Policymakers	
Culture	All	All	
Science	Academia, Industry	Academia, Industry	
Market User preferences		Utilities, TSO´s and DSO´s, demand Aggregators, End users, RES-generation owners	

Actors related to the socio- and orgware were mainly contacted with a geographical focus on German Germany in the context of the “Energiewende”. Additionally, actors from Austria and Switzerland were included to create a broader base for the inquiry. The choice of these countries is based on the fact that they share a common electricity wholesale market area with Germany. Furthermore, legal frameworks are comparable, and electricity exchange between the three countries is very high. An exception was the hardware circle strongly related to technology consisting of internationally distributed stakeholders as battery manufacturers and developers are active on a global level. The final list of included groups and their allocation with a short description and classification through the goggle of CTA (selector – enactor) is given in Table 5-2.

5.2 Format of stakeholder engagement

The survey served as a base for semi-structured interviews and was continuously enhanced during a pretest phase that consisted 3 phases. A first pretest phase was carried among 12 persons working in the broader field of energy systems (System analysis, energy storage, mathematics, technology assessment) at the Karlsruhe Institute of Technology (KIT) and Nova University Lisboa (UNL). All participants had the possibility to comment each question and criteria presented in the online survey. Additionally, to this step 5 informal semi-structured discussions were carried out. These conversations were based on the feedback and results participants gave in the before distributed survey and has led to an adopted list of stakeholder groups and reformulation of some questions and criteria. The talks had a duration between 30 to 180 minutes. Finally, all questions, stakeholder groups, and criteria were presented to the candidates working group (7 persons) to consolidate the inquiry.

Table 5-2: Classification of different stakeholders

Stakeholder	Allocation	Description
Utilities	Orgware – selectors	Generation, service, end user, infrastructure
Network operator	Orgware – selectors	Grid operation, infrastructure
RES production/retail	Soft and orgware – selectors	System integration, manufacturing, planning, operation
Energy Storage Business	Software - enactors	System integration, service, operation, planning, Lobby groups
Battery R &D (University)	Software - enactors	R & D battery technologies (electrodes, systems, electrolytes, etc.)
Research - Energy system (University)	software - selectors	System analysis and modeling, energy market modeling
Regulation	Orgware – selectors	Market rules, grid connection rules, etc.
Civil society	Software and socioware – enactors and selectors	Environmental conservation groups - NGOs
Battery manufacturer	Hard, Org- & software – enactors	Production, R&D, sales, system integration, operation
Automotive sector (electric mobility)	Software – enactors & selectors	System integration (vehicle), production, operation
Public body & policy making	Orgware & Software – selectors	Legal framework, subsidies,
Other	Various	Related to the topic

The second pretest phase included external experts (outside KIT and UNL) which were confronted with a more consolidated survey. A precondition for this phase was to contact at least one representative of all stakeholder groups within the seven socio-technical sub-regimes. The survey was distributed with individual emails to 22 experts within all socio-technical sub-regimes. The first contact briefly introduced the topic of the survey and possible interview. The mail stressed that the aim is to get critical feedback on the survey as well as to gather general expectations about energy storage. It also highlighted that no expert knowledge about electrochemical energy storage is required. Candidates were also asked if they are willing to participate in follow-up interviews. In total 13 external experts responded providing various comments and thoughts on the topic. From these ten candidates were willing to participate in an interview. An overview of the participants and the interviews is given in Table 5-3.

The interviews were conducted in a semi-structured way mostly via telephone due to the considerable physical distance of the candidates. Only one personal interview was conducted with a participant working in the same city. Each interview had a duration between 30 to 120 minutes and was conducted one to one. As mentioned before candidates were familiar with the overarching questions for the interview as they were provided in advance through the survey. The questions were not followed strictly, but they provided a structure for the individual development of each interview. It was guaranteed that the material would be used in an anonymized form without direct quotation.

The interviews started with a short introduction of the topic and then left the candidates space to introduce themselves and their field of work. This was flanked by questions about their profession. This has helped to achieve a more casual interview situation, and to surpass to a certain degree the non-personal character of a phone talk. It was recognized that all candidates answered questions very carefully in the first 10 minutes probably due to cautiousness. After 15 minutes, they opened and expressed more their own opinions. Leading topics were discussed between 20 to 40 minutes depending on additional questions based on the amount of feedback provided by each interviewee a priori. This was then followed by a less formal conversation about the research and the implications of it.

Table 5-3: Overview of interviewed actors

Index*	Organisation	Type	Organisation	Profession	Comment
P1RE	Private Research Institute	Enactor	Private Research Institute	Head of Energy department	Via telephone, ~40 minutes, notes
P2U	Utility company	Selector	Utility company	Head of department	Via telephone, ~50 minutes, notes
P3RES	RES System integrator	Selector	RES System integrator	Senior operation services	Via telephone, ~115 minutes, notes
P4U	Utility company	Selector	Utility company	Senior consultant	Via telephone, ~40 minutes, notes
P5U	Utility company	Selector	Utility company	Head for energy storage project development	Via telephone, ~50 minutes, notes
P6Reg.	Regulation agency	Selector	Regulation agency	Expert of the department of RES and energy efficiency	Via telephone, ~90 minutes, notes
P7Auto	Automotive	Enactor	Automotive	Vice head of project management	Via telephone, ~80 minutes, notes
P8ES	Energy storage business	Enactor	Energy storage business	Project management	Via telephone, ~90 minutes, notes
P9Ac	R&D University	Enactor	R&D University	Principal investigator energy storage research	Personal, ~80 minutes, notes
P10PC	Energy Policy consulting	Selector	Energy Policy consulting	Consultant & Professor @ Univ.	Via Telephone ~20 min, notes

*Index for every participant where RE=Private Research, U= Utility, RES=Renewable energy source, Auto=Automotive business, Ac=Academia, PC=Policy consulting

Hand notes were conducted with the ulterior motive to avoid guarded responses and maybe self-consciousness as in the case of recordings [5]. None of the participants refused this procedure. Notes were transcripted directly after the inquiry and included only the most critical points of the interviews.

This phase has led to further small alterations of the survey and offered valuable additional qualitative information about the questions raised. The responses are combined with the results of the survey in order to provide a deeper understanding of stakeholder's visions about the development of the sector.

The third phase before final distribution was a last technical pretest. The test was conducted with five persons of the candidates working group. It had the aim to avoid format and spelling errors in the final survey version and to test the connected MCDA model presented in chapter 6. After this loop, the survey was distributed to the previously identified persons and organizations.

5.3 Stakeholder consultation and participation

The pretest phase has led to a total number of 13 stakeholder groups. Candidates where approached based on 1) organization, 2) skills and 3) snowball principle as explained before. The first list of 81 stakeholders and organizations was developed based on internet research and business contacts. An internet research was conducted to identify organizations suitable for the inquiry. Identified organizations were contacted formally and were asked to forward the inquiry to contact responsible for the field.

Contacts related to point 2 were based on the candidates existing network. This network consists of a high number of experts from the field of energy storage, generation and RES through international conferences, workshops, and projects. Some events which have led to essential connections worth to be mentioned were among other things: Energy Storage World Forum 2014 in London; Armand Peugeot - International Conference "Electromobility: Challenging issues"; IEEE International Energy Conference 2014. Dubrovnik, Croatia; 4th International IEEE-Conference on Clean Electrical Power Renewable Energy Resources Impact (ICCEP) in Alghero, Sardinia 2013; "Energiewende - zwischen Konzept und Umsetzung." Bonn 2013 and IEEE International Energy Conference and Exhibition (EnergyCon), Florenz 2012 and others.

Finally, 106 persons were contacted directly via personalized emails naming the reason why the candidate has been selected for the inquiry, and 30 emails addressed organizations. One initial condition was to include about six persons per stakeholder group which was not achieved at the beginning. It was thus necessary to contact more experts in the areas where this was not achieved. Still, it was not possible to fulfill this precondition as feedback was very low in some of the stakeholder groups (e.g., public body & policy making). The total number of contacted experts was 136 and an estimated amount of about 100 persons included through forwarding the message to colleagues (communicated in response emails and total clicks on the survey of 272). In total 91 persons started the survey if second round pre-testers are included. 71 Persons finished the entire survey, while the remaining ones did only finish it partially. All stakeholders are categorized into the two categories of enactors and selectors as indicated in Figure 5-1.

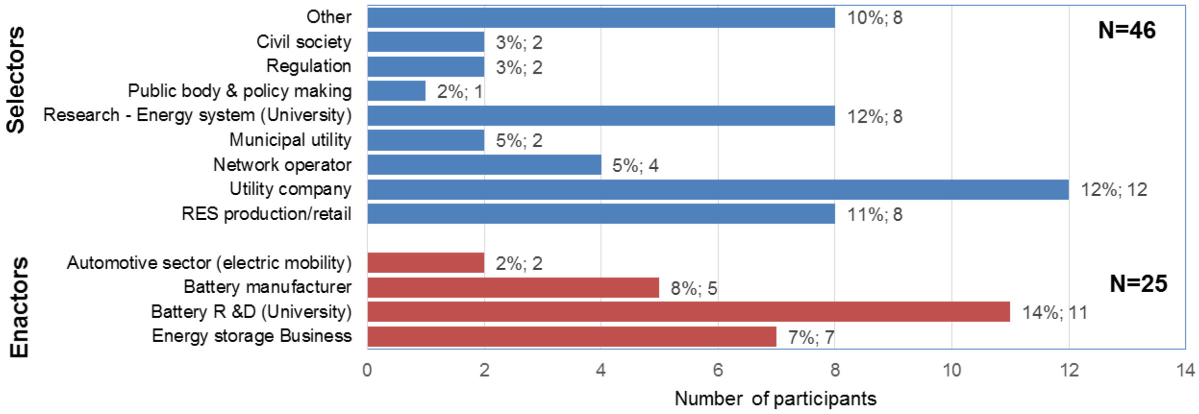

Figure 5-1: Total number of different participants including pre-testers of 2nd phase with n=71

Other stakeholders were three consultants, four power electronics manufacturers, one electrolyzer manufacturer (one unknown profession was excluded in total assessment). The most responses came from battery researchers (11), followed by utilities (12) and energy system research (8). The RES sector also had active interest in the topic (8). About five battery manufacturers and six experts from the field of energy storage answered the survey. The municipal utility (2), automotive (2) and policy-making group (1) had the lowest feedback rate. The feedback rates should be handled with care as they do not allow representative insights into the interest of different stakeholder groups in the topic. Feedback rate might be influenced by several factors, e.g. a number of colleagues informed. The self-assessment into one of the stakeholder groups can be tricky, this was stressed by some of the interviewed candidates. One stated that most of the municipal utilities are also network operators making it difficult to allocate oneself into the right field intuitively, what might explain the low feedback rate of this group.

The success of CTA is, of course, dependent on the willingness and openness of actors to use "spaces for broader negotiation processes. Participants of the survey were thus asked to voluntary indicate at the end their willingness to participate in an alternative interactive workshop and in follow-up interviews related to the recommendations found in section 3.5 (see Figure 5-2). Most of the actors would be willing to participate in such an event to gather more profound insights into the field. Especially battery manufacturers showed a high interest in such a format which contrasts with battery R&D.

Less than the half of all participants would then be willing to participate in follow-up interviews. In both cases, about half of the selectors and enactors would be willing to participate in a workshop. Willingness to participate in follow-up interviews for validation is slightly lower in relation to the former. Still, in both cases, it is believed that there would be enough participants available for a workshop and a handful of follow-up interviews to test if the CTA process has changed stakeholders view on technology (if they think differently about technology, are they more conscious regarding other criteria not considered before the process).

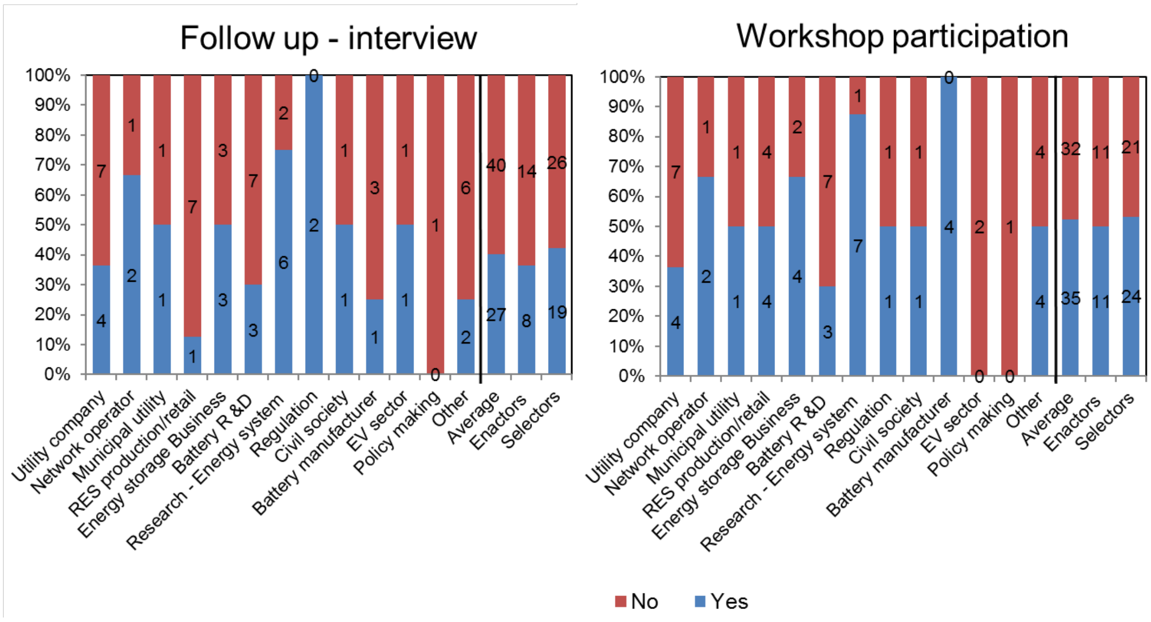

Figure 5-2: Willingness of participants to take part in an interactive workshop and in follow-up interviews with N=67.

5.4 General expert views on balancing options

The following section gives an overview about expert expectations on different balancing options and the role of battery energy storage in relation to these. Political and market aspects related to energy storage and changes of the electricity system towards more decentralization are given in the following sections and aim to construct the "evolving landscape." The last section analyses the perceptions on the importance of sustainability aspects for investments into balancing options, especially energy storage.

5.4.1 Expectations on balancing technologies

The interviews showed that all experts agree that there will be a need for balancing in the future. Indeed, there was no consensus about the amount, time frame or balancing options needed [P1RE, P2U, P4U, P8ES]. In general, some participants see a requirement for additional flexibility options at an RES share around 40 % which would correspond to the year 2025 regarding the analyzed studies in section 2.3. Expectations and visions of stakeholders about the need for balancing strongly correlate with the set of studies reviewed in chapter 2. There are though doubts about taken market assumptions [P5U] and considered business models [P2U] and [P7Auto]. One expert [P1RE] pointed this out as follows:

> *"… not clear how much balancing required…it is impossible to give robust statements about single technologies… not important as there will be a mix of different flexibilization technologies."*

This statement was underpinned by other interviewees as P4U by stating that the specific technology is not of interest out of a energy economic perspective. Interest is more nested in the bigger context with a general view on storage. It was furthermore stressed that balancing does not have to be provided by energy storage technologies as there are other options available [P1RE, P2U, P4U]. There are mainly four alternatives discussed in the community which are namely: 1) Grid reinforcement measures, 2) flexible demand, 3) flexible power plants and at the end of line 4) electric energy storage. The latter was divided into centralized (PHS, CAES) and modular storage/battery storage for a specific discussion with experts about the role of these among other alternatives. All addressed balancing options are seen as relevant, but expert's options differ on the extent of importance:

Demand side management: A significant problem regarding demand-side response is seen in end-user acceptance related to required smart meters and related high costs nowadays. This was especially pointed out for industry regarding the fear of losing to a specific degree control over their production [P7Auto]. There is only seen a small potential for DSM in the end-user and energy markets due to missing business cases and small profit margins [P6RES], [P5U]. One exception was mentioned using wall boxes to conduct DSM with electric vehicles [P7Auto].

Centralized storage (e.g., PHS and CAES): The potential for centralized energy storage especially PHS is viewed as critical due to severe acceptance problems of the public against new projects and high environmental legal constraints. At the same time, they are claimed to be the only economic viable option available nowadays facing an increasing cost pressure from markets [P10PC]. Existing PHS are already operating at the brink of being economi viable [P8ES], and potentials have already been exploited in the past [P8ES]. The technology may serve as a backbone for system stability in combination with decentralized storage options in the future [P10PC]. Other technologies named in the context of centralized energy storage were power to gas and hydrogen.

Grid Extension: is perceived as elemental to the success of the Energiewende. Despite the need for it, all experts argued that this option is highly unpopular within population making it difficult to realize necessary extensions [P3RES], [P7Auto], [P5U].

Flexible Power Plants: Experts stated that technologies as gas turbines are well known for their safety and low cost in relation to other options. There are furthermore no acceptance problems awaited as, e.g. in comparison to PHS. Nevertheless, some experts do not see this technology as relevant on the long term (after 2035 to 2040) [P8ES].

Battery storage: Experts have different opinions when it comes to electrochemical energy storage in comparison with other flexibility options [P10PC]. An often-named significant advantage for batteries in relation to other options are high-efficiency grades [P3RES] and modularity [P10PC]. Electrochemical storage is seen as crucial for specific niche applications especially for short-term applications as primary frequency regulation or uninterruptible power supply. Most interviewees doubted that battery technology could compete with any of the given alternatives due to their bad comparable economic performance [P9Ac]. Low economic performance is also often linked to concerns about sufficient cycle life time of most battery types. Thus, participants perceive them as not that relevant for the years to come [P3RES], [P8RES] and [P10PC]. High potentials are seen for battery storage in case of a decentralized energy system structure in combination with increasing market shares on electric vehicles [P8RES], [P7Auto]. This is mainly seen due to a more accessible realization of small multi-kWh units until the 2030ies and the possibility to adapt to increasingly dynamic market situations through the given modularity of batteries.

Some of the survey participants also added several flexibilization options in the comment area as follows: Power-to-heat, power-to-gas, Vehicle-to-grid, Flexible RES generation (e.g., curtailment & participation to balancing), Power conversion, P2heat and P2cold. Comments show that there is a plenitude of options available which are not considered explicitly in this work.

It can be said that some balancing measures are considered by experts as more intermediate solutions as transmission grid extension and flexible power plants [P8ES]. Most experts think energy storage technologies, including modular and centralized systems, are in general still too expensive in relation to the other options named [P8ES] [P10PC] and that there might be a too strong willingness of policy to support energy storage projects since they might "*bet on the wrong horse*" [P10PC]. A major problem attributed to the energy storage is not directly related to the technology itself but the absence of suitable business cases. The general need for energy storage itself is intensively discussed in the community [P1RE, P2U, P4U, P5U, P7Auto, P8ES] and the extent of the relevance of a balancing option should always be seen in relation to all available technologies [P8ES]. The lack of suitable business cases can also be transferred to all other technologies named, despite grid extension measures.

Participants were asked to attribute points to different balancing options in a 1-10 continuum between "low relevance," "Medium" to "high relevance" within the survey as depicted in Figure 5-3. A Mann-Whitney U-test is conducted to evaluate if there are significant statistical differences between enactors and selectors. The U-test is a non-parametric test which compares two groups response distributions by replacing original observations with an ordinal rank to form a test statistic [165]. It is one of the most used statistical tests used in case of the absence of normally distributed data or if there are notable differences in the number of subjects of two comparative groups [166]. Both circumstances are the case for the inquiry conducted. A p-value over 5 % leads to a rejection of the Null-hypothesis that groups have statistically significant different characteristics. The higher the value is, the higher the probability that the compared groups have the same distribution of responses. For the sake of reproducibility also Mann-Whitney U values (MW U) are given in the figure for comparison reasons.

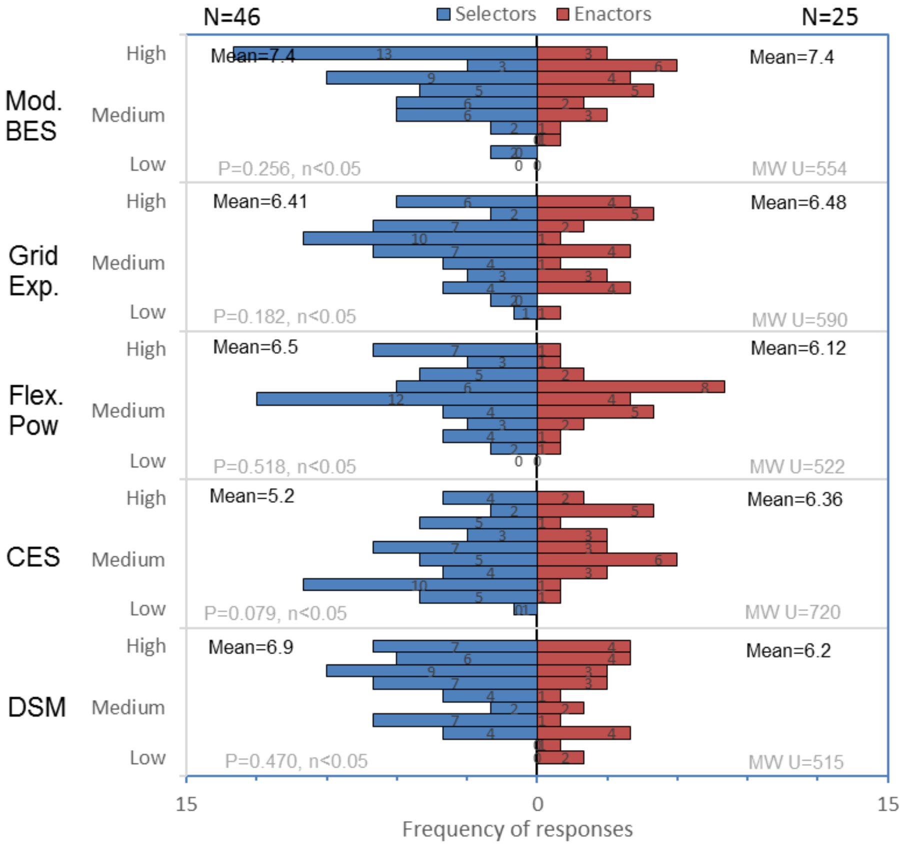

Figure 5-3: Relevance attributed to different balancing measures where Mod.Bes=Battery storage; Grid Exp.=Grid expansion measures; Flex.Pow= flexible power plants, CES=centralized energy storage and DSM for demand-side management

Different tendencies of enactors and selectors allocated to a specific technology are indicated by the mean value of ratings. Interviews give a somewhat pessimistic outlook for storage in general for the years to come; this comes especially true for batteries. It is thus interesting that both types of actors perceive battery storage as the most relevant technology among the other balancing options (7.4) in the survey. Especially the group of RES production and retail actors attributed a high score to batteries, maybe due to their interest in promoting stronger decentral structures with a high share of PV. This also comes true for participants from the automotive sector who see a high potential for synergy effects of electric mobility and battery storage.

All participants have a rather pessimistic view of the role of larger energy storage units. This perception seems is especially shared by utility companies which may have bad correspondent experiences and corresponds well with the insights given in the interviews. Other measures as DSM and Grid expansion measures have comparable ratings regarding their importance (high with a mean value from 6 to 7). In total, notions about the relevance of unique technologies seem to vary a lot among the groups. Still, the U-test has shown that the observed differences in all cases between the two groups in the sample are not statistically significant.

5.4.2 General expert views on market and policy aspects

Most of the participants perceive balancing technologies, especially energy storage as an essential precondition for the success of the German energy transition, but don´t see a high potential for these in the years to come. An often named reason for reluctant investment activities is the absence of commercial and legal incentives. This results from the fact that stakeholder roles are not really established and continuously shaped and regrouped [121]. Yet no really socio-technical regime has been established when it comes to energy storage. Further discussion was thus based on the question if RES impacts on markets and system stability are underestimated on a policy and market level. The aim of the question is to explore policy and market conditions under which storage technologies will be introduced into the energy system in the frame of this transition and which may be seen as an obstacle.

Participant P10PC stated that the market impacts of RES are well understood and that most of the relevant studies published in the last five years go in line about the effects of RES on wholesale markets and related implications for energy storage. On the other hand, RES growth was underestimated in the last five years. Transmission grid operators did, e.g. not anticipate the number of grid congestions and dispatch costs related to the system integration of wind and PV [P10PC].

There are thus doubts among experts regarding the predicted RES shares until 2030 due to missing strategies to achieve RES goals on a policy and regulation level. These concerns are primarily connected to the German Renewable Energy Act (Gesetz zur Förderung erneuerbarer Energien –EEG). Not only EEG regulations have to be improved, but markets, as well as the legal framework of the electricity grid as actors, think that impacts are underestimated on multiple levels. A representative statement was given by P5U as follows:

> *“…. The energy turn-over will work… but not in the way it is propagandized by the government …with an 85 % RES share target… it is completely illusory regarding the catastrophic market situation…and missing regulation….already 40 % RES shares will lead the market and system to tumble…then we might have a problem if not storage is available… market and EEG regulations have to change to maintain system safety”.*

The EEG is considered as a key to energy storage success, in the sense that it should attribute more personal responsibility to RES and energy storage asset owners. Especially regulation for residential storage and the obligation of (more) direct marketing of RES [P5U] were named as crucial aspects to foster new business models. Such regulations should also include third parties that provide direct marketing services of RES generated electricity in combination with energy storage [P5U]. Experts also stress that changes in regulations should not only happen on a national level but on a European scale. This statement is reinforced by P3RES, P9Ac, and P7Auto, addressing lack of suitable overarching strategies on a policy level and regulation as follows [P3RES].

> *“.. it is underestimated to a certain degree… policy actors have learned from the past … EEG was adopted to minimize RES growth to take pressure from grid operators…the measure does not work… RES still grow and still no overarching strategy…Is available”*

On the other hand, there are also other views on the role of regulation which is not seen as a necessary measure to steer energy storage development [P5U]. This notion is reinforced by a statement from a survey participant claiming that decentralization and democratization of electricity production should not be hindered through legal regulation as it is the case for PV nowadays.

The magnitude of interviews [P3RES, P7Auto, P2U, P4U, P8ES] agreed that market situation in Germany should change in frame of the Energiewende. Even mature energy storage technologies as

PHS are operated sharply on the threshold of being economically viable due to increasing market pressure. Most experts claimed that there are several storage technologies already existent nowadays, but that there is no business case and only insufficient market regulations available. The value of storage cannot be directly allocated to one actor as there are several beneficiaries of services provided (e.g., storage in combination with wind energy direct marketing leading to transmission and distribution upgrade deferral). This is problematic as the investment in storage is conducted by one party. Thus, storage services provided should be accordingly rewarded which is not the case nowadays [P7Auto].

Actors named different measures to tackle these challenges reaching from a new way to calculate margin costs within the merit order model, new forms of auctioning models [P5U], up to the formation of capacity markets [P8ES]. In this context, some actors claimed that available energy models do not account changes in market design and broader technology use. Stakeholder P5U claimed that market models have a short validity because it is unclear if market clearing prices and margin costs will be calculated the same way in 2030. Further doubts are also related to the underestimation of dispatch costs and grid congestions. This is on the one hand based on the logic of applied energy models that use a “copper plate” grid approach and don´t consider these effects [P10PC]. Furthermore, short-term fluctuations are often not adequately considered as hourly time steps are used in most modeling approaches [P5U]. The magnitude of the interview partners seemed to agree that some studies may systematically underestimate storage technologies.

The results of the survey give a more moderate view in relation to interview impressions as indicated in Figure 5-4. All participants had the possibility to rate if they entirely agree (5) or not (1) to the given statement (if RES impacts on markets and system stability are underestimated on a policy and market level). Half of the selectors (25) agreed to the comment whereas only ten enactors did. It is notable that about 18 participants did not agree with the statement and that in average enactors seem to have a slightly neutral view on this statement (average 3.1). The reason for this discrepancy could be based on the fact that this some participants of the group are either not so familiar with overall system challenges or that they do not perceive them as critical. The U-test has shown that there are no statistically significant differences between the two groups due to a p-value above the significance level of 5%.

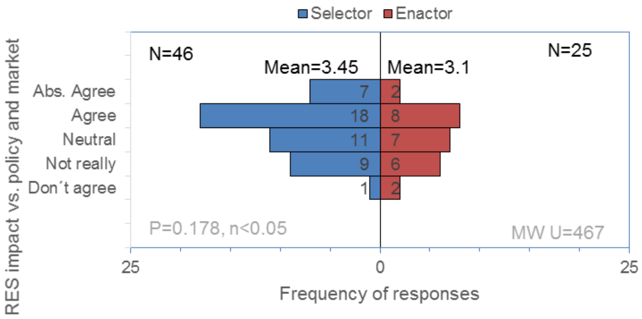

Figure 5-4: Agreement on the statement that Impacts of the “Energiewende“ on markets and system stability are underestimated with n=71

5.4.3 Expert opinions about decentralization and balancing options

The next section addressed potential changes regarding the architecture of the future energy system. These changes are related to markets, ownership structure and developments of the electricity grid towards smart grids and more decentralization with a highly integrated bi-directional flow of information, money, and energy between customers where the entire energy system becomes more complex through the inclusion of new technologies as storage or electric vehicles. Such future energy systems are told to offer new potentials for DSM, energy storage and battery systems [167], [32]. The next question thus aimed to find out about how strongly actors agree that the energy system will be decentralized and if this offers new possibilities for energy storage options. There was a strong consensus in favor of this statement among the interviewees P9Ac, P3RES, P4U. Especially participants from utilities explained that they are conducting own research in the field of decentral energy systems and electric mobility to explore new business potentials. Participant P3RES noted that especially industry is increasingly building up own generation units to optimize own power consumption. Interviewee P5U expressed his approval in a representative form as follows:

> *"… the future system will become more small sized… with a higher degree of individual responsibility*[29]*… and more benefits on a local level…end users have to be integrated in a stronger way…only this and not regulation itself enables the integration of balancing measures as batteries, demand-side management and others.."*

Some experts see these changes on the long term until 2050 and believe that there will be a balance of central multi MW and small multi kW power plants as a kind of transition phase after 2030 up to the year 2050. Within this time frame, large investments in the field of GW units are told to sharply decrease due to increasingly dynamic and uncertain energy market conditions [P6Reg] and [P10PC]. PV, batteries and electric vehicles are seen as a significant driver for this development [P7Auto]. It also clear that the establishment of decentralized systems may require new local market structures which provide benefits for a specific region. This process is seen as a complex task where local actors have to be integrated and to provide business models which enable it to generate benefits for them [P5U]. Also, such concepts would require the integration of new players as third parties who coordinate marketing and provided services by storage [P5U].

The survey results underpinned this impression as indicated in Figure 5-5*.* The magnitude of both groups agrees to this statement, whereas only four do not. It could be proven that tendencies slightly vary across groups, as indicated by different average values, but that there is no significant statistical difference among them as p>0.5.

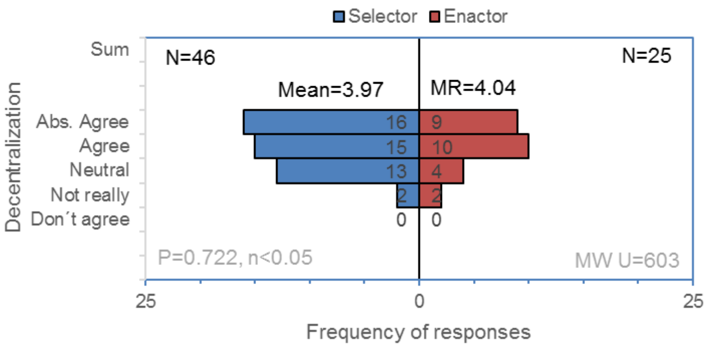

Figure 5-5: Agreement on the statement that the future energy system will be strongly decentralized

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[29] In the context of local energy consumption and regulation

5.4.4 Relevance of sustainability aspects for investment in balancing options

The literature claims that investment decisions related to energy technologies are strongly based on sustainability aspects which reflect the need of society [168]. This claim might be true considering a policy level, e.g. the EU directives 2001/77/EC or the target formulation of the German federal government regarding the "Energiewende." The specific question was thus if "sustainability" aspects (environmental, economic and social factors) should play a more significant role in investment and research decisions regarding balancing options. It had the aim to see how actors think in general about fitting technology to societal needs. The question was thus deepened in the interviews and extended by asking them if sustainable development is already a task in pragmatic decision making in day to day business.

All participants intuitively agreed that sustainability aspects are an essential factor that should be considered in a stronger way in the future [P7Auto, P2U, P5U, P6RES]. Deeper discussion showed that most interviewees relativized their first intuitive notion after a certain time as P7Auto:

> *"Of course everybody would intuitively say yes, of course, it is important, but… social justice or ecologic compatibility are not a major topic in companies day-to-day business... Only if there is a possibility to generate competitive advantages….The availability of resources and a guaranteed future are of course important but mainly out from an economic perspective."*

The discussion showed that none of the actors would increase the sustainability of a product due to altruism on a business level. In contrary, it was stated that actors go out all to exhaust existing legal frames and regulations to generate competitive advantages. The statement from the literature that decisions related to RES are highly driven by sustainability might be true on the first view but are in their core more complex. Interviews showed that notions about sustainability are characterized by a deep dichotomy. This circumstance is expressed by P3RES as follows:

> *"Definitely … it (sustainability) is very important! …We are already working in the field of RES, so I guess we already contribute to sustainability…but we have to sell our products as cheap as possible… there is a strong competition, and at the end, only prices count in the field of RES."*

All experts are aware of the importance of sustainability aspects but do not explicitly consider them on a pragmatic business decision level. In case, notions about different dimensions of sustainability are always implicitly connected to economic motives. One Actor argued for example that his company included three different sustainability factors into technology-related decision making namely; CO_2-emissions, cost, and resources [P2U]. These three factors can also be seen as primary economic input parameters for margin cost calculation and thus form the base of investment calculations nowadays[30]. It is thus assumed that sustainability aspects are probably the least motivation for using these indicators.

Participant [P10PC] stated that the importance of different sustainability dimensions would increase in the future. The example of social acceptance is seen as very important as local resistance against a project may lead to delays in planning. Similar statements were also named regarding environmental

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[30] Generation units margin cost are mainly calculated on base of fuel prices (resources), CO_2 certificate costs and maintenance cost.

aspects (especially regarding the Umweltverträglichkeitsprüfung/Environmental review by officials). Thus, the implicit motivation is again based on economic interest. It seems that actors from science have a different perspective. They perceived sustainability as more important but also attributed themselves a higher degree of freedom as they do not face economic pressure and competitiveness as stakeholders from industry [P1RE and P9Ac].

The results of the survey in Figure 5-6 show that the magnitude of 32 stakeholders agrees strongly with the statement. About 26 agreed with it while only 10 remained neutral, and three did not agree. This results give the impression, that sustainability is considered as very important within the entire sector. A certain skewness can be observed towards higher importance on the aspect in the group of selectors in relation to enactors (mean value 4.33 and 4.04). None of the participants disagrees entirely with the statement.

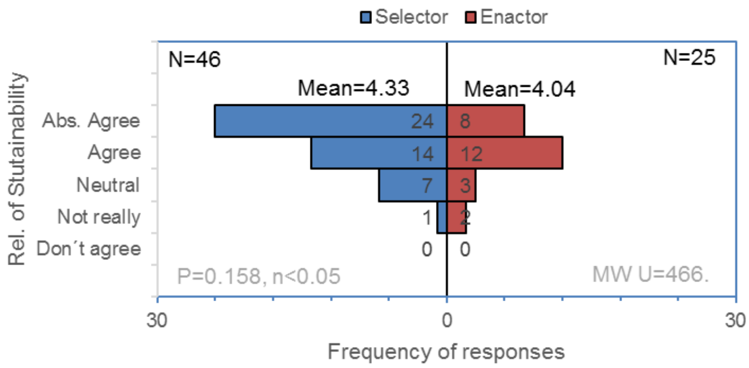

Figure 5-6: Indication about the statement that sustainability (economic, ecologic and social dimension) should play a more significant role in large balancing technology investments and research (n=71)

The Mann-Whitney U-test indicated that there are no significant differences between the two groups. However, results are characterized by a certain degree of inconsistency when they are compared with the interview results. Statements have shown that actors agree intuitively to the statement but implicitly always refer to the economic sphere of sustainability. It is assumed that results in the survey are to a certain degree a product of un-reflected and somewhat arbitrary answers as sustainability is seen as a desirable and normative state by a high magnitude of participants.

5.4.5 Summary of expert views on balancing technologies

The need of energy storage technologies is highly discussed among enactors and more actively across selectors, not in the sense if they are required but when and in which amount. Energy storage technologies represent one balancing option among others which are namely; 1) Grid reinforcement measures, 2) flexible demand, 3) flexible power plants and at the end of line 4) electric energy storage which itself can be separated into modular and centralized storage. Experts expressed general doubts about the economic viability of energy storage itself in relation to these other balancing alternatives as there are no suitable business cases and regulations available. There is no high potential seen for centralized large energy storage technologies (it remains unclear if large battery storage units are also included here). A comparable high relevance is attributed to modular energy storage/battery systems in the survey but interviewed experts perceive them as one of the most expensive technologies and don´t attribute them a high relevance in the next ten years to come. There is a high consensus among all participants that it is hard to make any robust estimations regarding energy storage technologies due to missing business cases and regulatory frameworks.

Significant issues named are missing regulations within the EEG, wholesale market structure and the absence of an overarching European strategy to achieve a 100% RES share until 2050. Experts perceive these issues intuitively as an obstacle for broader market introduction of energy storage technologies of any kind. It can be derived from the inquiry that changes in the architecture of the energy system towards a more decentralized system and resulting lower large-scale investments might represent a big opportunity for battery storage in the mid- (2035) to long-term (2050). It remains unclear if this process leads to market changes and how new business models will look like in such a system.

The inclusion of different sustainability dimensions into investment decisions for balancing measures is seen as intuitively crucial by almost all participants. Interviews have shown that both actors, selectors, and enactors tend to go out all to exhaust existing legal frames and regulations to generate competitive advantages [P7Auto]. In general, sustainable development is instead seen as a normative state with low relevance on day to day business decisions for technology-oriented actors.

5.5 Specific expectations on electrochemical energy storage systems

In general, Experts claimed that it does not make sense to go into detail of different battery technologies as the entire topic of energy storage remains blurry and complicated for them. Instead, they proposed to make a more general approach and not to focus on single electrode chemistries but just to refer to batteries in general. The first section will focus on the expectations and visions about the use and location of battery storage systems. The second section will highlight the views of stakeholders to the selected properties of battery storage systems.

5.5.1 Expert views on stationary battery applications and system integration

There are already various battery technologies available that can be considered as mature, but they are not seen as profitable nowadays by the interviewees as there are no reasonable business cases available [P7Auto] and [P3RES]. Market diffusion of battery storage is not seen as a disruptive event, rather an incremental process over the next ten years [P7Auto]. This development is seen as highly dependent on market frame conditions, namely energy prices and availability of regulations. Experts state that batteries can provide high power as well energy and can be scaled depending on a given business case making the technology very flexible [P9Ac], [P10PC]. Defining which battery type may be suitable for a particular market is considered as a challenging task due to the different properties which each technology inhibits. Especially cost and life time issues in relation to DoDs and categorization of application fields are named as a factor of uncertainty [P5U]. Following discussions with experts are thus centered on the suitability of the following five different potential business cases.

Decentralized storage on a distribution level nearby demand within a storage range of multiple hours is seen as a vast market for battery storage in Germany. Especially the combination of storage with decentralized renewable energy sources as photovoltaics was named by all interviewees. PV has already reached grid parity in Germany due to high end-user electricity prices (up to 30 €c/kWh). Self-consumption is thus seen as a practical way to reduce energy cost. The field of self-consumption in combination with PV and batteries is also expected to be also very interesting for mid- and large-scale industry companies. Participant P10PC stated that in 10 years PV systems would in general only be sold in combination with battery systems. It was also stressed that the area of decentralized storage can also be combined with wind, DSM and other alternatives.

Further diffusion of stationary battery systems in this area is told to be highly linked to market diffusion of electric vehicles. The market introduction of EVs is seen as a way to reduce costs in battery production [P7Auto]. The Tesla power wall and Mercedes “Heimspeicher” were named in the frame of this discussion [P2U], [P7RES]. The automotive and PV industry was told to be one of the leading lobbying groups in Germany to push forward residential storage and governmental subsidies to enter a new market segment. They are considered to become one of the leading gainers from this development [P2U], [P5U].

New decentralized concepts: P3RES proposed new business models in the broader field of self-consumption as leasing contracts for entire systems that could attract potential customers in this field by avoiding high up-front investments. Especially new concepts as virtual power plants offer utterly new business possibilities for scalable battery storage [P5U]. Such concepts can also focus on using batteries to smoothen local energy demand as a DSM measure using different end-user tariffs. Battery owners might, for example, receive a price forecast curve which is then matched with real-time curves and finally inverted via a battery system to save energy cost [P5U]. The problem is that the composition of these decentralized systems itself is in their infancy. Interviewee [P7Auto] proposed that it would make sense to offer entire packages as a business model. Such packages should consider PV, DSM, and storage in a sense that the entire system becomes economic vaiable. A significant problem with such systems is that there is no adequate remuneration for provided services. An example of not rewarded indirect services through storage is the avoiding of additional investments through municipal utilities in distribution grids.

Generation near energy storage on a mid- to high voltage level is believed to be an interesting field for stationary batteries, but only in combination with RES [P3RES], [P5U], [P10PC] and [P8ES]. One of the main advantages in this context is seen in the scalability of battery systems allowing it to adapt to market situations. RES direct marketing was named to become a significant area in Germany since EEG tariffs were drastically reduced. A significant advantage for batteries in this application is that they can be built up nearby generation units offering advantages as increasing efficiency and operation conditions [P3RES], [P10PC]. However, electricity wholesale market prices in the near future are considered to be too low for such an application as they would not cover present storage cost [P6Reg]. Another argument for generation near storage was named by [P5U] through avoiding local T &D upgrades almost always required at new RES grid connection nodes. There might be the possibility in the view of the interviewee to combine direct wind marketing and, e.g., T&D deferral and help to save costs for TSO´s and DSO´s.

Day-ahead market arbitrage business on a multiple hour level on a transmission grid level is not seen as reasonable for battery storage out of an economic view [P7Auto], P10PC], [P8ES]. PHS represents the absolute reference for this case and batteries are not considered in any way as a competing technology. Nevertheless, interviewee P5U stated that there might also be a potential for battery storage in day-ahead markets. This potential is not seen by using hourly based time steps to exploit on- and off-peak spreads but to use short-term 15-minute time steps following price curves more strongly influenced by meteorological forecasts. There is no study available that would underpin a useful application of batteries in this field [P10PC].

Short-term balancing is seen as a very lucrative application for battery storage as they offer the possibility to mitigate deviations very fast on nearly every time and grid-scale [P9Ac]. Applications for ancillary service provision only require short storage times and high power rates. This meets halfway the central issue of battery costs which strongly correlate with storage capacity [P10PC] making battery storage economic viable within a short time. The case of primary regulation is seen as the most promising battery application in the field nowadays [P10PC]. A high potential is again seen in the future use of smaller battery storage units within virtual power plants which provide balancing services (so-called pooling) [P5U].

On the other hand, participants stressed that it is difficult to make a general statement about business cases as the questions are strongly related to different technologies. An example expressed here fore was that RFB has completely different storage times than a Li-Ion battery [P3RES], [P5U]. Nevertheless, seconds to multiple hour applications as RES balancing, e.g., on a distribution level are seen as the most interesting area for battery technologies within the interviews [P3RES]. In general, most participants perceive missing valuation of provided energy storage services as a primary obstacle for market diffusion of stationary batteries. The stacking of services as a business model is seen as an important issue but has to be elaborated in detail in the future [P5U] and [P10PC]. One participant (network operator) of the survey commented this as follows:

> *"Each party uses it for its value, integration of these values could generate a more efficient system approach."*

Experts were also asked to rate the relevance of different storage timescales and linked application cases for electrochemical energy storage on a scale from 1 (low relevance) to 5 (high relevance) as indicated in Figure 5-7. Again, mean values are used to compare group preferences.

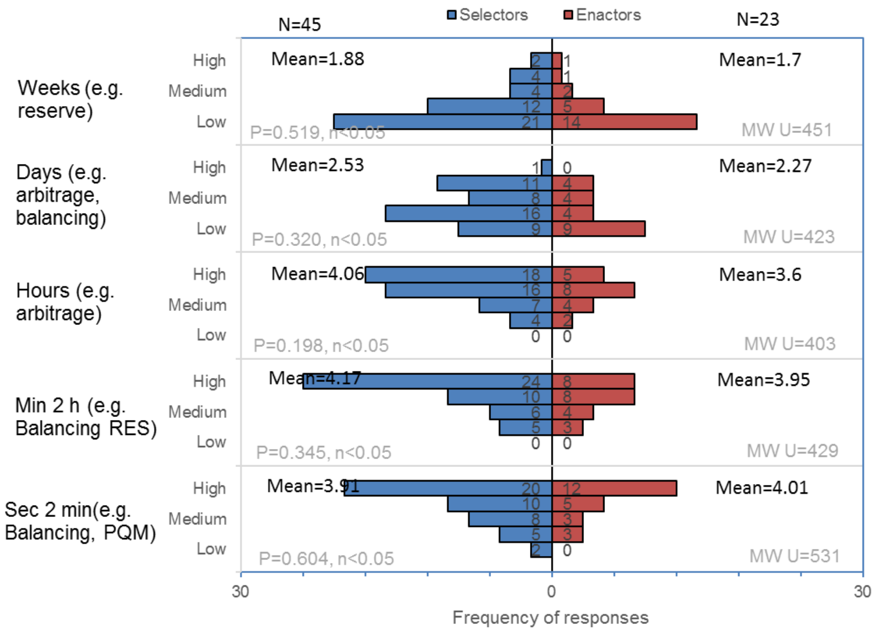

Figure 5-7: Potential application fields for battery storage

There is almost an equal ranking of preferences among enactors and selectors regarding the different storage dimensions. Seconds up to several hours and even days are seen as suitable timescales for battery storage which was also flanked by a statement of a survey participant (network operator):

> *"Not yet profitable ... after expected price decrease range from seconds until days could become profitable for batteries."*

All experts agreed that there is no viable business case available for long-term storage applications up to weeks. Results from U-test indicated that there are no significant differences between the two groups regarding all application fields.

In general system integration of battery storage is naturally dependent on the suitability of a given business case as discussed in chapter 5.5.1. Battery storage is mainly seen on a decentralized level nearby local renewable-based generation and users [P2U], [P7RES], [P5U]. Some participants from the survey (battery manufacturer and Network operator) underpinned this by comments as "location nearby decentral industry" for the provision of regulation services. Experts have different views on the integration into other grid levels, especially into transmission grid level. Most state that there will be nothing like bulk storage through large battery banks connected to the high voltage grid [P10PC], [P3RES]. Generation near integration of battery storage for conventional power plants is considered as not probable whereas a combination with large-scale RES as wind turbines or ground-mounted PV is seen as more suitable on a multi-MWh scale.

Experts were asked to indicate the probability of different system integration levels for electrochemical energy storage on a Likert scale from 1 (very unlikely) to 5 (very likely). Integration of battery storage technologies is considered to happen mainly on a distribution (<10 kW) and mid-voltage level (<1 MW) as depicted in Figure 5-8. Generation side applications (alongside large generation units >1MW) are ranked before the use on a transmission grid level (e.g. T&D deferral with >1 MW). The latter is considered as rather improbable in the frame of the interviews due to actual regulations related to unbundling. Survey results do indicate a more neutral stance of stakeholders regarding this integration level. Again, the U-test indicated that there are no significant differences between the two groups regarding all application fields.

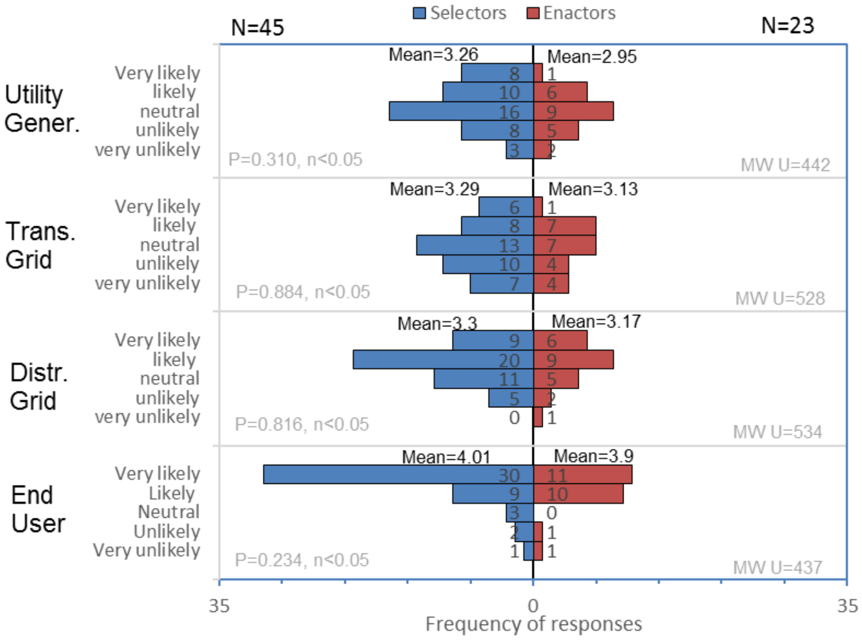

Figure 5-8: Potential system integration level for battery storage including mean values;

5.5.2 Expectations: properties and development of stationary battery systems

Most participants agreed that high costs are the most significant problem of available battery technologies and that they have to decrease in the future. There are doubts that this will happen for all electrochemical energy storage systems in the years to come [P10PC], [P3RES] and [P5U]. Scale effects through electric mobility are considered to have the potential to considerably lower cost for Li-Ion based systems. In general, most participants see a demand for further research efforts to lower battery system cost [P3RES], but the absence of viable business cases seems to be a more critical issue.

The issue of calendric and cyclic life time is considered as a central problem [P10PC], [P3RES], [P8ES] and [P5U]. Interrelation of both factors, costs and life time, is seen as a complex task. The prolongation of life time can be achieved by oversizing of the battery, but this causes additional cost [P10PC]. At the same time, the relation of depth of discharge (DoD), calendric as well as cycle life time and implications on overall storage cost remains unclear. An example named in this context is primary regulation which is characterized by several cycles per day with a low DoD and the question how this impacts battery life time and consequently overall cost. The issue of missing knowledge about cycle life time and DoD relation hinders potential investments in the area [P5U]. The issue was addressed in a representative way by an example about RFB expressed by P9Ac:

> *"…RFB can have around 10 k cycles in general… it will change if you configure it for a high power application … so you would have to add cells again to increase cycle life time, and that would, of course, increase cost…"*

Participants agree that battery systems can be optimized [P9Ac], [P5U] and [P10PC]. This optimization should start in the production phase and the targeted application area to identify room for improvement. The cathode is seen as the most expensive factor from a narrow point for most systems. It makes thus sense to see if a high-power variation is needed. Most stationary applications do not need them, and they can thus be excluded in most cases. Such measures are, again, highly dependent on the technology and application field in scope and are finally guided by costs [P9Ac].

Energy density is in general seen as an essential factor for battery storage but not for stationary applications as these are characterized by a low degree of restrictions on weight or space. Power density is perceived as more critical especially when it comes to short-term balancing [P9Ac] as in the case of primary regulation. The relevance of this property is thus dependent on the viewed business case. Efficiency degrees are also named to have significant importance, especially when battery storage is compared with other balancing options [P3RES], [P10PC]. In general, all of the named aspects are seen as relevant and highly interdependent from each other [P8ES].

Used materials for electrode manufacturing constitute a critical factor for market success [P5U], [P10PC]. There are concerns about potentially harmful materials used in the manufacturing of certain battery technologies. This comes mainly true for applications situated nearby the end-user in decentralized applications. The toxicity of used materials in PbA (lead) and potentially VRFB (H_2SO_4) is for example seen as problematic by experts in this context [P5U]. Thus, technologies should be thoroughly tested before they are used nearby to consumers [P10PC]. There is, in general, a need to make people more aware of the potential environmental dangers of electrochemical storage as expressed by [P5U]:

"…if you have … let´s say 300 MWh redox-flow battery … with a large number of toxic materials…you need some risk management…"

The availability of critical materials used for electrode manufacturing was also named as an essential issue. In the frame of this discussion, recycling is seen to be important if there are materials included in a battery that are worth recycling them. There is for most technologies a lack of available recycling processes (despite PbA), but the aspect will become more relevant when more cells are produced of a specific battery type [P9Ac].

The perceived relevance of different aspects influencing the future investment decision in battery storage was ranked in the frame of the survey within a range of low, medium to high on a 1 to 10 scale. The results are indicated in Figure 5-9, where the mean values indicate tendencies of the two related groups. Cost factors are not addressed directly in the survey but are included as a criterion within the multi-criteria decision-making analysis. Results from the survey indicate a comparable picture to the interview statements. Calendar and cycle life time are perceived as the essential property of battery storage technologies, followed by efficiency, power density and recycling and energy density.

The Mann-Whitney U-test showed that there are no significant statistical differences between the two groups regarding the expectations of battery storage properties.

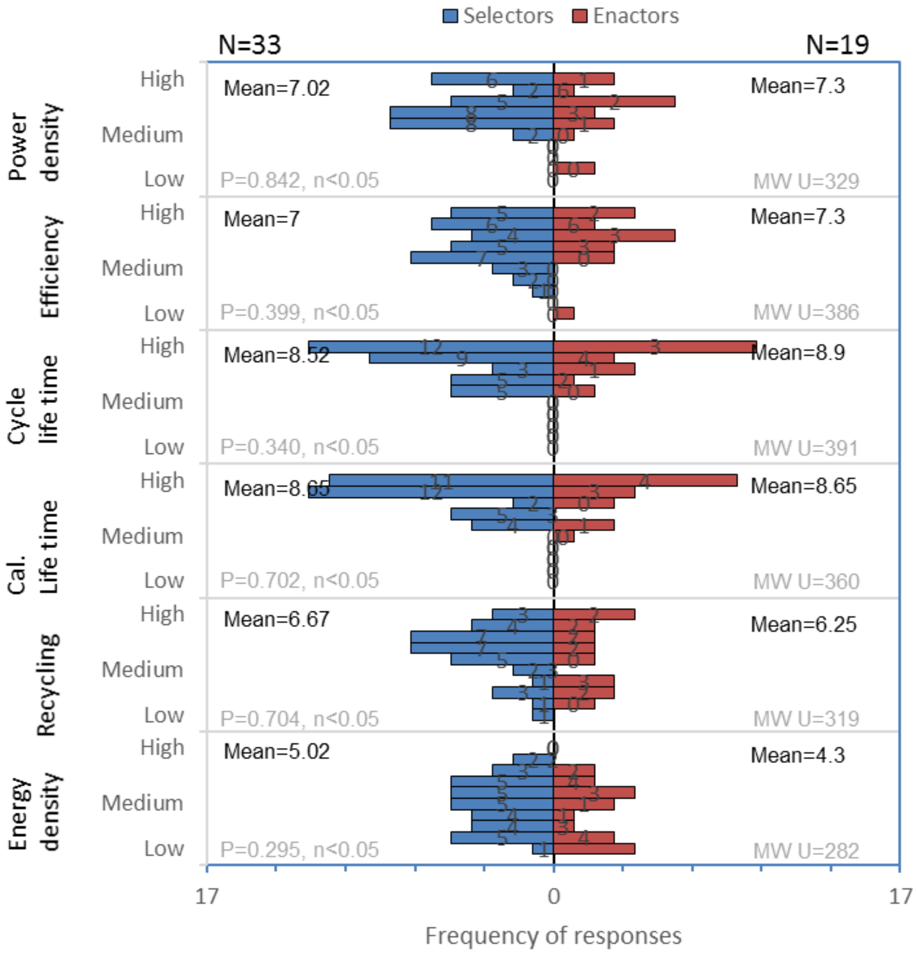

Figure 5-9: Importance of battery storage properties for stationary applications rated by experts on a scale from 1 to 10 (low, medium, high)

5.5.3 Summary of expert expectations on battery storage

Participants did not show interest in single chemistries but the performance of different batteries as they do not see commercially viable business cases for them. Market diffusion of different battery storage is seen as an incremental process over the next ten years, closely linked to electric mobility and decentralization of the grid. Battery system integration is considered to mainly happen on distribution and mid-voltage level and in some cases transmission grid level alongside with RES sources as wind turbines. Significant potentials are seen in storage times between seconds up to some hours, e.g., for ancillary service provision depending on the used technology. Experts struggled to allocate battery technologies into specific applications due to their different properties and resulting economic viability. Especially DoD to cycle life time implications and their impact on overall system cost are named in this context. These factors are understood as a central challenge in the next years. Possibilities for cost reduction are seen through scale effects and optimization of cell manufacturing. Potential toxicity of used materials is of major concern, especially in consumer near applications on a decentralized level but also when a high magnitude of capacity is required. Most stakeholders perceive more research in the field as a prerequisite for the success of battery storage technologies.

5.6 Summary and implications for further assessment

The preliminary interviews with various actors are used in combination with the insights from the literature review to structure the domain of energy storage and overall landscape developments and to form an overlying narrative for battery storage development within the German energy transition as indicated in Table 5-4.

Table 5-4: Results of interviews and surveys to structure the domain of flexibility demand and battery storage

Landscape aspects	**Questions discussed**	**Interview and survey results**
System-level developments and implications for energy storage in general	RES impacts on the German energy system considering 100% target in 2050	- **Enactors and selectors mostly agree** - RES impact underestimated to certain degree, especially on a system level but not a market level
	Demand for balancing	- Is expected to grow strongly after 2025 to 2035 - Strongly dependent on overall power system design
	Will the future energy grid be decentralized?	- **Enactors and selectors strongly agree** - Grid considered to become more complex - Higher role of small generation as PV and Wind - No largescale generation expected after 2040 due to increased risk through volatile markets
	Availability of market regulations (e.g., capacity market) **for energy storage**	- **Enactors and selectors strongly agree** - Markets (capacity markets, spot markets) and regulation (EEG) have to change - Market pressure very high, new structures required - No viable business case available for energy storage o No valuation of benefits (in general)
	Role of **battery energy storage** among other flexibility options (power grid extension, demand-side management, flexible power plants)	- **Enactors and selectors mostly agree** - There will be an interplay of all four options - Battery storage is seen as too expensive at the moment - No competition for other options today - However, battery technologies are considered as most important technology among other options on the mid-term (see survey in 5.4.1) - Incremental market growth is seen over next ten years - Growth-linked to electric mobility and residential storage o Automotive sector as key for market diffusion o Tesla and Mercedes are named in this context - Decentralization provides potential for battery storage o New business models o Modularity allows adapting to market
Relevance of sustainability	Relevance of sustainability for flexibility option development, investment, and use	- **Selectors agree strongly, enactors agree** - Seen as a normative goal, not relevant nowadays - Perceived to become more critical in the future, - Factors as local acceptance are seen as crucial

The process of decentralization and electric mobility are seen as a core for the success of battery storage. Significant concerns are not directly related to the technology itself, instead the absence of viable business cases is considered as problematic. The relevance of sustainable development is thought to become higher in the future.

The second part of the stakeholder engagement focused explicitly on electrochemical storage properties and potential applications. The discussion is structured mainly around five topics also identified preliminary in the literature (see chapter 2.8.3); technology, economics, environment and application fields as depicted in Table 5-5, whereas social factors as acceptance were only mentioned by actors on the brink. The table is separated into critical issues named by actors and expectations and visions that correlated to these.

Table 5-5: Specific results regarding electrochemical energy storage technologies

Center for discussion	Critical issues for battery storage named by actors	**Expectations and visions:**
Technical drivers	**Relevant properties:** - 1 st Calendar and cycle life time, 2nd Power density & 3rd efficiency, 4th recycling ability & last energy density - DoD-Cycle impact unclear o Comes true especially for different applications	- Structuring of electrodes possible for optimization o power density named as an example o Cathodes are seen as most expensive component - SoC management to extend battery life time
Economic drivers	- Up-front investment still too high for some actors - Unclear interaction of life time and cost o Especially for different applications o There is no viable business case available making predictions difficult	- New business models as leasing could tackle this issue o Avoiding up-front investment o Sell entire "packages" (PV+DSM+storage) o New third parties provide services - Adopt EEG to create economic stimulus - Optimization of cell manufacturing for specific application - Scale effects through EV markets
Environ-mental aspects	- Risk management regarding toxic materials needed - Environmental dangers (Electrolyte or electrode material) - Recycling of critical materials - Doubts are especially centered large-scale storage units	- Monitoring required to avoid damages - Recycling processes will only be available for materials that are worth recycling
Social aspects	- Acceptance is seen as high in general, - Use of critical material problematic - Decentralized end-user near applications critical	- Comprehensive monitoring of potential dangers to guarantee acceptance
Application fields	- Which technology in which application? - It is claimed that no viable business case is available - Mainly short-term and decentralized applications - Stacking of services required	- Enactors and selectors mostly agree - Bulk storage/arbitrage business (1/4 h) - Short-term application (sec- to minutes) - Decentralized / application o new applications - Generation near storage (for RES)

However, the results from the interviews and the survey show that there are different application cases discussed. Decentralized applications are seen as most interesting application field in the future. This is also in line with the "master narrative" where decentralization of the grid is seen as a leading driver for battery storage technologies in the future. The DoD-cost relation is considered as critical and difficult to estimate, especially when different application cases are considered. These aspects make it difficult to allocate different battery technologies into a particular application field. Major issues related to the environment are centered in toxic materials, recycling of critical materials and environmental dangers.

These doubts are highly related to the application (e.g., nearby end-users, large-scale storage). Comparable statements come also true for social aspects.

The in-depth insights about electro-chemical storage obtained through stakeholder engagement serve as a base for the further specification of sub-criteria used for MCDA. Naturally, implications for technology evaluation arise through the predefinition of criteria within the MCDA-process as different system analysis models must be fitted and found accordingly to these. Table 5-6 provides some fundamental implications identified for the MCDA and technology evaluation conducted in chapter 6 and 7.

Table 5-6: Basic implications for MCDA and technology evaluation

Aspect	Implications for MCDA and technology evaluation set-up
Technical drivers	- Inclusion of this DoD-cycle relation for storage operation simulation - Testing of importance of parameter relevance
Economic drivers	- LCC to analyze cost-life time provide detailed information - Investment cost analysis
Environmental drivers	- LCA-approaches provide general picture related to environmental dangers - Toxicity and recycling processes are difficult to evaluate (lack of data)
Social Aspects	- To be tested
Different use cases	- Comparison of technologies used in different applications under consideration of DoD-Cycle relation, cost and environmental impacts - Focus on decentralized application

6 Multi-Criteria-Decision-Making model

The main challenge to select or to develop best alternatives for energy storage within the “Energiewende” is to “*pick the winners*” at a level of society [140]. The identification of criteria and methods that “measure” sustainability is a prerequisite to explore technology performance. Technology development is an evolving process constructed through a social process in which scientific and expert knowledge is combined with the preferences and values of affected communities to enable a co-produced understanding of preferred outcomes [7]. Using principles of CTA offers the analytical achievement of shifting the loci of the assessment through the inclusion of enactors and selectors to obtain a broader perspective and to avoid thinking in enactment cycles.

The addressed problems in this work include several alternatives and a high degree of uncertainty about the prospects of emerging energy storage technologies on a system level. Multi-criteria decisions analysis methods (MCDA) offer a way to aid such complex decision-making problems transparently. They provide formal mechanisms based on mathematics to integrate stakeholder preferences objectively and to make decision processes more transparent as well as debatable.

The first sections give an overview about the field of MCDA and the structure of the proposed model. AHP in combination with Shannon Entropy, alpha and beta diversity is introduced in the following section. After this, the Technique for Order Preference by Similarity to Ideal Solution – TOPSIS is highlighted as an aggregation method. This is followed by a description of the selected criteria and alternatives. Finally, an overview of the developed model and its realization is given.

6.1 MCDA: A short introduction

MCDA is considered as a branch of operation research models that deal with decision problems involving multiple criteria. Literature offers a separation of MCDA methods into Multi-Objective Decision Making (MODM) and Multi-Attribute Decision Making (MADM). The first set of methods handles decision problems where the decision space is continuous. MODM aims to find an optimal solution space in consideration of predefined boundaries [104]. Typical examples are mathematical programming or maximum vector problems with multiple objective functions [169].

Methods within MADM concentrate on problems with discrete decision spaces where a set of decision alternatives has already been predetermined. In general MADM problems can include *m* alternatives which are evaluated on *n* criteria which can be expressed in a grouped decision matrix as follows [8]:

Criteria C_1 ... C_n

(Weights w_1 ... w_n)

Alternatives - --- --- - --- ---- --

$$X = \begin{array}{c} A_1 \\ \vdots \\ A_m \end{array} \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix}_{mxn}$$

x_{ij} .....$Performance\ of\ the\ j-th$ of the $\mathrm{i}-\mathrm{th}$ alternative

w_j ....$weight\ of\ criteria\ j$

$n\ is\ the\ number\ of\ criteria$

$m\ is\ the\ number\ of\ alternatives$

Figure 6-1: Example for a decision matrix (based on [8])

MADM refers to “attributes,” “goals” and “alternatives.” “Attributes” are considered as “objectives,” “factors” or “criteria,” e.g., economic performance and environmental impact. “Alternatives” is synonymous with technology “option,” “policy,” “actions” or “method” [170], [171]. Each method has a "goal" or general objective of the decision process. Criteria related to the problem are located beneath to this goal. These criteria can be further decomposed into sub-criteria which also can be seen as constraints or refinements [101].

An advantage of MADM is that criteria with different scales or units can be simultaneously compared. This work compares a limited predefined set of emerging technologies with other mature technologies that can be delimited from each other. These technologies are evaluated based on different sustainability oriented criteria. The contribution of each technology to achieve this goal can be measured on different scales. Thus, this work fulfills all preconditions to apply MADM. The use of MODM methods is more suitable to optimize systems through the combination of a high number of different technologies for a future energy system [104] which is not part of this work.

A question that remains is which kind of MADM should be applied in the context of this work? This is an often underestimated or just ignored issue within the field of MCDA [172]. In general, MADM can be separated into classic compensatory approaches or multi-attribute utility theory methods (CCA) (American school) and outranking approaches (OA) (European school) [104], [172], [171] [8].

CCA assigns a utility value to each alternative. The total utility is the sum of marginal utilities that each criterion assigns to a considered action [173] and is known as a single synthesizing criterion. These methods offer a total preorder of given alternatives. Typical methods are MAUT (Multi-Attribute Utility Theory), SMART (Simple Multi-Attribute Rating Technique) [174], TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [153] and AHP (Analytic Hierarchy Process). It is claimed by literature that the level of aggregation within the American school of MCDA is a disadvantage due to the loss of information and that they do not accept that there are good reasons to justify the incomparability of two alternatives. The decision maker furthermore admits that an absolute compensation can exist between the different evaluations. Thus a good performance for one criterion can easily be counterbalanced by another poor one [172]. This can lead to the choice of a non-optimal alternative that might have a good performance on one specific criterion but a bad one on the remaining others.

OA seek to eliminate alternatives that are in a particular sense dominated. References are used to give some criteria more influence than others [171]. Some concepts available to establish such relations are thresholds, concordance, and discordance. Typical methods are ELECTRE I, II and III (ELimination and Choice Expressing REality) [173] and PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations) [104]. Concerns about OA are centered around the dependency on rather arbitrary definitions of what constitutes outranking and how threshold parameters are set and later manipulated and that they lack an axiomatic basis [172].

An overview and summary about some typical methods within different MCDA claims are given in Figure 6-2. A good comparison of different methods is given in [172], [101], [104], [171] and [175] and is not provided in this work.

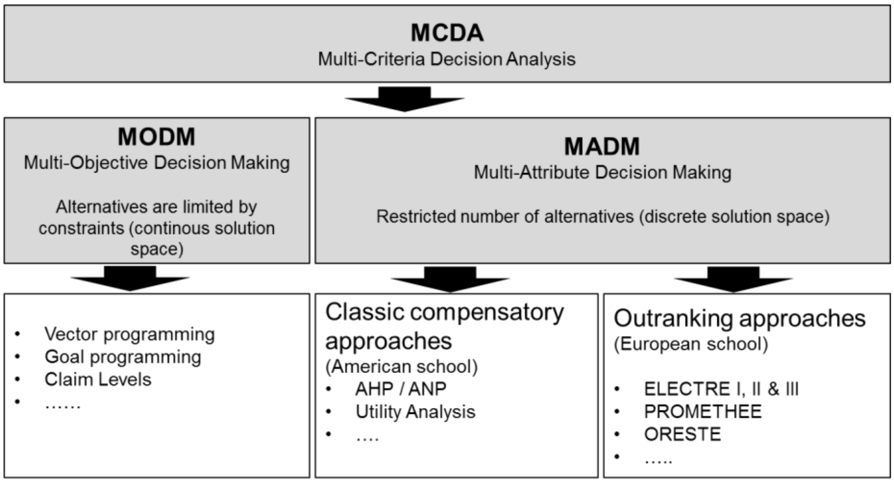

Figure 6-2: Categorization of MCDA methods

6.2 Choice of an MADM method

In general, all MADM methods have their theoretical and pragmatic limits and are more or less adequate for different decision problems. They can be roughly schematized by a construction phase (input data and the modeling phase that includes the interface to stakeholders) and an exploitation phase (aggregation and calculation leading to recommendations). This separation shall serve as a base to elicit an adequate method.

The first phase of MADM is highly dependent on the mode of preference articulation which plays a critical role in the entire decision-making process. Often used elucidation modes are tradeoffs, direct rating, lotteries and pairwise comparisons. This work aims to include a high number of participants, various criteria by a survey and a limited set of semi-structured interviews. One has thus to consider the limitations on human performance described in the literature of psychology which are named as cognitive spans (memory span, attention span, perceptual span, etc.). These limitations refer to the amount of information or distinctions that can be grasped by a stakeholder at once as a base of making judgments [176]. It has furthermore to include several complex criteria based on different qualitative and quantitative types of data. The following basic requirements have been defined for the construction phase of an MADM method for this research:

- limited potential for actor consultation due to time restrictions
- has to include quantitative and qualitative data
- has to consider blurry and uncertain data
- measure different data on one scale
- provide all the information required for a stakeholder to express his preference adequately
- elucidation method that is easily understandable and intuitively usable by the participants

The exploitation phase requires a method that allows the aggregation and calculus of preferences. There are several multi-criterion aggregation procedures (MCAP) available within MADM [172]. The requirements on MCAP for this work are:

- handle a high number of input numbers of multiple stakeholders (> 50)
- allow an assessment of group decisions

- be implementable within a justifiable time
- provide transparent and easily understandable results

MADM methods initially tested[31] where ELECTRE I [173], SMART [174], TOPSIS [153] and AHP (Analytic Hierarchy Process). Requirements for the construction as well exploitation phase make the expression of trade-offs required for OA methods only partially possible. The tested method of ELECTRE I required some time for programming and was not considered to be practical for a high number of participants and the limited possibility of interaction with these. Finally, a mixture of AHP and TOPSIS was considered as a most suitable approach.

6.3 AHP-TOPSIS model

An overview of the MCDA model including all steps and methods (numbered from I to III) is given in Figure 6-3. AHP makes it possible to structure complex decision problems by a hierarchic structure easily. The phase of obtaining stakeholder priorities by pairwise comparisons within AHP is seen as an intuitive and easy way of elicitation. The choice of proper criteria is an integral part of the first step in the entire MCDA model. All selected criteria are explained in detail and quantified in chapter 7.

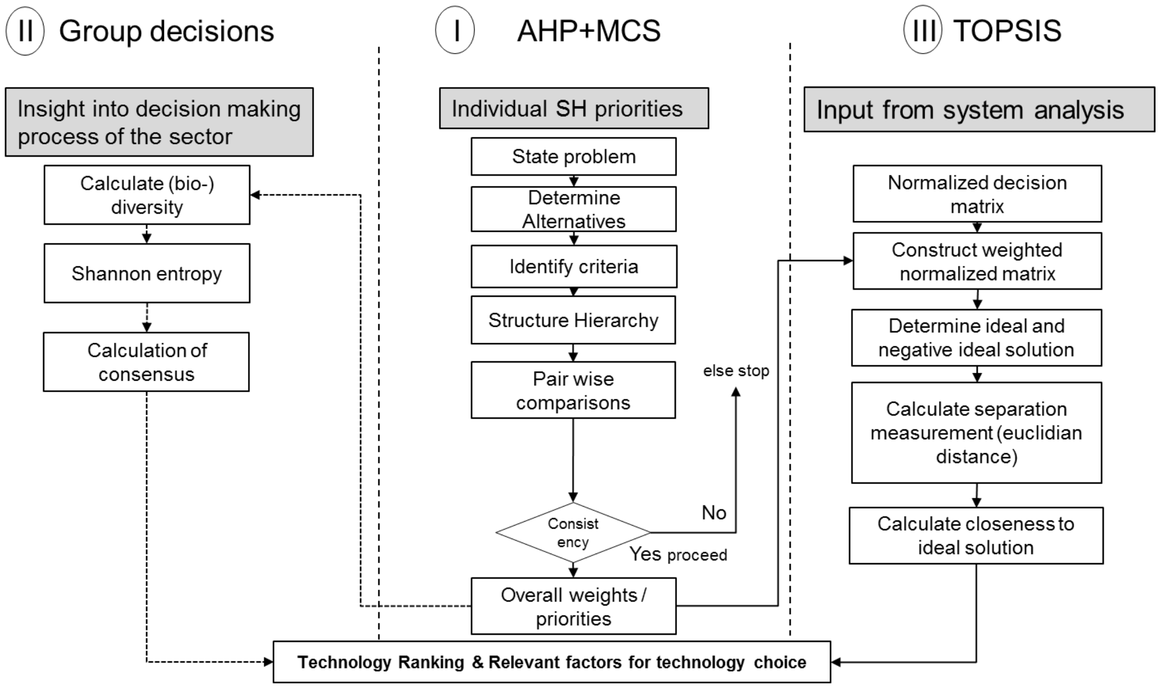

Figure 6-3: Scheme of the adopted MCDA-model for energy storage technology evaluation

The results of AHP are furthermore used to calculate an index that describes the consensus among all participating actors in respect to their perceived stakeholder group using concepts of bio-diversity (alpha and beta diversity) and Shannon entropy (see II in Figure 6-3). This helps to identify if there is something as “shared expectations” regarding the relevance of different criteria for sustainable development of storage technologies within the different stakeholder groups (see section 6.3.2). The derived priorities from AHP serve as input for Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for

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[31] Within FCT-UNL MAD classes

result aggregation (see Figure 6-3 III). TOPSIS allows a fast and straightforward calculation of rankings using the calculated priorities from AHP as well as to combine them with the results from system analysis and is explained introduced in chapter 6.3.2. The entire MCDA model was implemented in Microsoft Excel and Visual Basic.

6.3.1 The Analytic Hierarchy Process

In general, AHP represents a non-linear framework for carrying out both deductive and inductive thinking, considering several factors simultaneously, allowing for tradeoffs to arrive at a synthesis [151]. The method is based on mathematics and principles of psychology. It is a compensatory method which allows numerical trade-offs among various dimensions.

AHP requires the establishment of a hierarchic or a network structure representing the problem [177]. This is simply done by decomposing and structuring the given decision problem into different levels within a hierarchy. At the top of this hierarchy is the general objective of the decision process (e.g., choice of technology or policy). Criteria related to the problem can be found below this goal and can be further decomposed into sub-criteria. Finally, competing alternatives can be found at the bottom below the lowest-level criteria (e.g., some technological artifacts) ([101], [177]) as depicted in Figure 6-4. This structure allows it to mix quantitative and qualitative data and is easily over-seeable.

A restriction of the hierarchic structure is that any criterion of one level has to be capable of being connected to an element in the next higher level. The latter represents a criterion to assess the relative impact of elements in the level below [170].

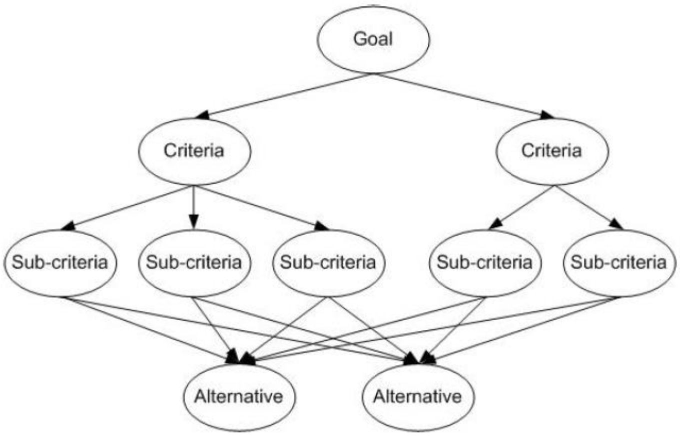


Figure 6-4: Construction of a hierarchic structure for AHP

Comparisons based on a 1-9 Likert scale of absolute numbers have to be carried out to gather the relative importance of each criterion after establishing a hierarchic structure. The fundamental question for pairwise comparisons is: *how many times more important is one element than the other concerning a specific criterion or attribute*? This comparison expresses the preference to a specific attribute assigned by an individual or a group of participants [170]. The use of pairwise comparisons in AHP is considered to user-friendly and understandable from a participant perspective. The number of pairwise comparisons n_c is dependent on the number of considered criteria and can be calculated by the use of Eq 1:

$$n_c = \frac{n(n-1)}{2}$$ *Equation 1*

When all comparisons are made a scale of priorities is derived on the base of the relative dominance of these preferences. The relative importance of two compared criteria is scaled in a fixed continuum from 1 to 9 as depicted in Table 6-1.

Table 6-1: AHP pairwise comparison scale based on [8]

1	Equal importance	Two criteria contribute equally to objectives
3	Slightly more important, weak moderately	One criterion is slightly favored against another
5	Moderately more important, essential importance	One criterion is moderately favored against another
7	Strongly more important, strong importance	One criterion is strongly favored over another
9	Extremely more important, absolute importance	One criterion is favored over another with the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent scale values	Used to represent compromise between priorities listed above

AHP requires a MxN matrix where $M$is the number of alternatives and N the number of criteria. The matrix is constructed by pairwise comparisons that provide the base for a square matrix in which a_{ji} represents the weight ratios (w_j/w_i) for each object $A_1,\ldots..,A_n$. The remaining matrix elements represent the reciprocal property of the matrix through $a_{ji}=1/a_{ij}$ and $a_{jj}=1$ [170] [177] as depicted in Eq. 2 [152]:

$$D = \begin{array}{c|ccc} & A_1 & \ldots & A_n \\ \hline A_1 & w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \ddots & \vdots \\ A_n & w_n/w_1 & \cdots & w_n/w_n \end{array}$$ *Equation 2*

There are several prioritization methods available in the literature, but only a few provide corresponding factors that allow it to evaluate inconsistency within judgments [178]. Inconsistency is a consequence of the attempt to derive a priority through the comparison of two objects at a time. These objects may be involved in several comparisons on a non-standardized scale, where relative values are assigned as a matter of judgment where inconsistency may occur. Some inconsistency measurement methods to be named are arithmetic mean method, characteristic root methods, least square methods [8] and geometrical mean method. In the classic AHP approach priorities are obtained by the so-named Eigenvector method (EVM) by solving the eigenvector problem. The need for a corresponding factor called Consistency Index (CI) for inconsistency evaluation results from the fact that individual judgments never agree entirely. A reciprocal comparison matrix can be considered as consistent when $\lambda_{max} = n$ and CI converges against zero. Inconsistency is faced in case of a high positive value. Consistency of priorities is additionally measured by a consistency ratio (CR) to avoid order dependency. The random consistency Index (RI) for matrices of order n represents the expected value of CI corresponding to matrices of n, when judgements are simulated and EVM is used as prioritization method. The CR gives information if judgements in the pairwise comparison matrix are consistent or totally random. In case of the latter comparisons have to be repeated, or as in this work be excluded. A high CR value reflects inconsistency and a low one the contrary case. [177] suggests a rule of thumb of 10 % (CR<0.1). More recently it was proposed to use thresholds of 5 % and 8 % (for 3x3 and 4X4 matrix). If this conditions are satisfied a decision or prioritization of actions can be made else the procedure of judgements has to be repeated [152], [103]. A detailed description of the mathematical procedures are given in [152]. Using EVM as a prioritization method has shown to be extensive in terms of calculation time when it comes to a high number of participants. Furthermore, CR rules were not satisfied for a high number of judgements and should thus have been repeated. This was not possible as AHP was carried out by an anonymous survey. The hurdle of 10 % is also seen as too restrictive by literature out of a practical view [179].

A more suitable method that meets the requirements and allows it to evaluate inconsistency is the geometric mean method (RGMM) [180]. It is considered as that RGMM does as well as EVM or even better than it regarding rank reversal and other aspects [180]. The phenomenon of rank reversal is caused by the addition or deletion of an alternative and can lead to a shift of the final ranking of alternatives and will be addressed in chapter 6.3.3.

The work of [178] proposes the use of a geometric consistency index (GCI) and provides approximated thresholds. The approximation corresponding to CR of ≤0.1 are: GCI=0.31 for n=3, GCI=0.35 for n=4 and GCI=0.37 for n>4. These thresholds are calculated for each participant by the use of Eq. 3:

$$GCI = \frac{2}{(n-1)(n-2)} \sum_{i<j} log^2 e_{ij} \qquad \textit{Equation 3}$$

Where $e_{ij} = a_{ij} w_j / w_i$ is considered as the error obtained when the ratio w_i / w_j is approximated by a_{ij}. Further information about GCI-calculation and theory can be found in [178] and [180].

6.3.2 Consensus on criteria importance

AHP offers the possibility to make the prioritization of technology criteria through an actor more transparent. As stated in chapter 3 sustainable technology development can be seen as a process of community-based thinking and learning. It was thus of interest for this research to gather a picture of consensus among stakeholders allocated to different clusters, precisely between enactors and selectors. The degree of consensus is seen as an equivalent to the degree of "sharedness" of expectations among stakeholders expressed through the judgments carried out in AHP and represents the level to which a group is "satisfied" by a decision. This requires that judgments are homogenous or align, in the sense that priorities expressed by individual group members are compatible with the group priorities [181]. Further investigation for group dispersion and group judgments for AHP can be found in [181] and [182].

This approach follows the idea expressed by [179] using the concept of diversity in biology and ecology. The original idea of this concept is to describe species richness and relative abundance and can be related to the priorities obtained through AHP. There are several diversity indices as Gini-Simpson, HCDT entropy x or Simpson concentration x available. A more profound insight into the introduction of true diversity in the form of a mathematical framework is given in [183].

The concept allows it to derive a consensus indicator S* to elicit actor preferences in numerical terms situated in a continuum between 0 to 100 %. The interpretation depends on the particular requirements within a group. The Indicator S* is based on Shannon entropy *H* [184] that can be used as diversity index for the distribution of prioritization of criteria using Eq. 4 [184], [183]:

$$D = exp(-\sum_{i=1}^{N} p_i \, ln \, p_i) = exp(H) \qquad \textit{Equation 4}$$

Where p_i are the calculated priorities for i=1 to N and true diversity of order one (D) [179]. Shannon entropy is expanded through the introduction of alpha and gamma diversity to compute S* following Eq. 5:

$$S*=\frac{\left[M-\frac{exp(H_{\alpha min})}{exp(H_{\gamma max})}\right]}{\left[1-\frac{exp(H_{\alpha min})}{exp(H_{\gamma max})}\right]}$$ *Equation 5*

Where $M = (1/\exp(H_\beta)$ is a reciprocal of beta diversity representing a simple homogeneity measure [179] [183]. H_β is the difference between H_γ and H_α. M represents the maximum numerical scale for the maximum possible priority of a criterion (in this case the Saaty scale with M=9). The $H_{\alpha min}$ is minimal if a SH fully prioritizes one criterion. Minimum alpha entropy $H_{\alpha min}$ and maximum gamma entropy $H_{\gamma max}$ for C criteria and K decision makers is computed following Eq. 6:

$$H_{\alpha min} = -\frac{M}{C+M-1} ln\left(\frac{M}{C+M-1}\right) - \frac{C-1}{C+M-1} ln\frac{1}{C+M-1}$$ *Equation 6*

and Eq. 7:

$$H_{\gamma max} = (C-K)\left(-\frac{M}{C+M-1}\right) ln\left(\frac{M}{C+M-1}\right) - \left(\frac{n+M-1}{C+M-1}\right)\left(ln(\frac{1}{n}\frac{n+M-1}{C+M-1})\right)$$ *Equation 7*

The Indicator can be seen as a measure of evenness of priorities obtained from the AHP process. A concentration of priorities of fewer or same criteria among stakeholders leads to a higher S*. The consensus of a group is low when the indicator converges against zero if priorities are distinct and high when priorities of SHs are identical [179].

6.3.3 Aggregation method: TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution - TOPSIS is an MADM method built on the idea developed by [153] that a chosen alternative should have a minimum distance to the positive idea solution A^* and a maximum distance from the negative ideal solution A^-. The principle is simple: the selected best alternative should have the shortest distance from the positive ideal solution in a geometrical sense while it has the longest distance from the negative ideal solution. This distance can be described by the Euclidian distance as depicted in Figure 6-5.

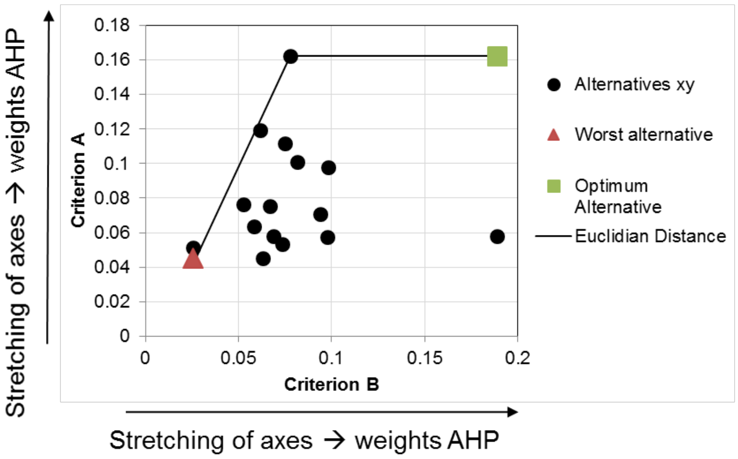


Figure 6-5: Schematic overview of TOPSIS

A decision matrix has to be established in TOPSIS including all alternatives A_1, A_2,…A_m over each criterion c_1, c_2,…c_n [186]. The first step is to normalize the given decision matrix $R = r_{ij}$ by the use of Eq. 8.

$$R = \frac{c_{ij}}{\sqrt{\sum_{j=1}^{m} c_{ij}^{2}}}, \qquad i = 1, \dots, m, \;\; j = 1, \dots n. \qquad \textit{Equation 8}$$

The next step is to multiply this matrix with its associated prioritization w_j provided by AHP to determine the stretching of the axis of normalized value v_{ij} (see Figure 6-5) [185] by the use of Eq. 9.

$$v_{ij} = w_j * r_{ij}, \qquad j = 1, 2, \dots., n; \qquad i = 1, 2, , \dots.., m. \qquad \textit{Equation 9}$$

The next step is to determine the ideal alternatives A* and negative ideal alternatives A$^-$ by the use of Eq. 10 and 11 where J represents a benefit criterion and J^- a cost criterion [186]:

$$A^* = \{v_1^*, v_2^* \dots \dots, v_j^*, .. v_n^*\} = \{(max_i v_{ij}^* | j \in J), (min_i v_{ij}^* | j \in J^-)\}\; i = 1, 2, \dots, m \qquad \textit{Equation 10}$$

$$A^- = \{v_1^-, v_2^- \dots., v_j^-, \dots v_n^-\} = \{(min_i v_{ij}^* | j \in J), (max_i v_{ij}^* | j \in J^-)\}\; i = 1, 2, \dots, m \qquad \textit{Equation 11}$$

After establishing negative and ideal solutions separation measurement using n-dimensional Euclidian distance D_i^* to calculate the distance of each alternative and ideal vector A* given by Eq. 12.

$$D_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^*\right)^2}, \qquad i = 1, 2 \dots. m \qquad \textit{Equation 12}$$

This has also to be carried out for the separation for each alternative from the ideal negative solution A- by Eq. 13

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \qquad i = 1, 2 \dots. m \qquad \textit{Equation 13}$$

The last step required is the computation of the closeness to ideal solution CIS and to finally rank the performance order by the use of Eq. 14:

$$CIS_i^* = \frac{D_i^-}{D_i^* + D_i^-}, \qquad i = 1, 2 \dots. m \qquad \textit{Equation 14}$$

It is clear that $CIS_j^* = 1$ if $(A_i = A^*)$ and that $CIS_j^* = 0$ if $(A_i = A^-)$. Ranking is carried out by the descending order of CIS_j^*, where the highest value represents the better performance [187]. As explained before TOPSIS also inhibits the danger of rank reversal [188], [186]. Two fictitious alternatives including values $\{Min_c, Min_c\}$ and $\{Max_c, Max_c\}$ were thus introduced following the recommendations of [186]. These values remain fixed so any valuation in reference to them cannot change. Distances D_i^* and D_i^-related to different alternatives A remain unchangeable and do not depend of performances nor on the introduced number of alternatives.

6.3.4 Choice of energy storage alternatives

Four principal battery chemistries were mentioned in the interviews and in the reviewed literature: Li-Ion batteries (LIB), Lead-Acid batteries (PbA), high temperature sodium-sulphur batteries (NaNiCl), and Vanadium redox flow batteries (VRFB) [P10PC], [P3Res], [P9Ac], [P5U], [P2U], [P7 Auto]. These are the most common battery types for stationary energy storage nowadays. PbA is the most mature electrochemical storage technology, which is used for a high quantity of power system applications [77] as local power quality, stabilization of grid extension, frequency stabilization [24]. Lithium-Ion batteries are seen as one of the most relevant technologies for stationary applications followed by vanadium redox flow batteries [P9Ac], [P10PC].

The inquiry has a strong focus on electrochemical energy storage; there are however different application areas in which battery storage competes with other technologies such as compressed air energy storage (CAES) or pumped hydro storage (PHS) which are included in one application scenario. An overview of all considered technologies is given in Table 6-2.

Table 6-2: Choice of alternatives for comparison

Alternative	**Sub-Categories**	**Stakeholder & Literature**
Li-Ion batteries	NCA, LFP, NMP, LTO	High considered potential
High-temperature batteries	NaS and NaNiCl	Seen as mature technology
Redox-Flow batteries	All Vanadium	High potential due to high flexibility
Lead Acid	Valve regulated Lead acid	Seen as most mature technology.
Pumped hydro storage	-	Seen as reference technology
Compressed air storage	Diabatic	-

6.3.5 Choice of criteria for electrochemical energy storage

In general, the success of an MCDA is extremely dependent on the effectiveness of the used criteria that correspond to the problem and the fulfillment of an objective [168]. The formulation of the problem and related criteria is more challenging than its solution which is a matter of math or skill. The choice of proper criteria represents the most exciting step within MCDA [172] and was an integral part of the initial pretest survey and the semi-structured interviews.

It is not given that the inclusion of a high number of criteria is helpful for decision making regarding sustainable development. In contrary, a low number of sufficient criteria can be more beneficial for an evaluation. The choice of proper criteria for technology evaluation can be linked to 5 principles [8]:

1) Systemic: Criteria should reflect essential characteristic of technological systems
2) Consistency: Criteria should be consistent with the decision-makers aim
3) Independence: Criteria should not include relationships at the same level criteria
4) Measurability: Criteria should be measurable in quantitative values or qualitatively expressed
5) Comparability: Decisions are more rational when comparability of criteria is more obvious

It is difficult to follow all these principles and not to select minor criteria. The selection of criteria is furthermore often characterized by a certain repeatability as including job creation and social benefits of a technological alternative (see section 2.8.3 and Table 2-9).

The actual literature on the topic provides a high magnitude of indicators which can be adapted and combined regarding specific objectives [115]. A first set of criteria based on the literature review in chapter 2.8 and the four main criteria, environment, economy, social aspects and technology was presented to 12 persons and discussed with five of these. Afterword’s 22 external experts were contacted and asked to conduct a critical review of the given criteria in a first round (see also chapter 5.6). In a further loop, a set of 8 participants was willing to take part in an interview to discuss the criteria. A last critical round was conducted in 2 follow up Interviews. A summary of the final primary and sub-criteria is given in Table 6-3; a more detailed discussion is given in the technology evaluation model in chapter 7.

Table 6-3: Summary of used criteria for technology evaluation

Main criteria	**Sub Criteria**	**Unit**	**Description**	**Comment on changes**
Economic	Investment cost	€/kWh €ct/kWh	All cost for project implementation Includes all cost over entire life time	OPEX was removed, as they were perceived as redundant
Technology aspects	Maturity	- MW 1-3	Track-record of a technology - Global capacity - Technology life stage	- Reformulation of flexibility, initially composed of 5 factors (combability, universality, modularity), - - Performance factors introduced later as – even if to a certain degree redundant – most actors sought them to be of high importance for separate evaluation
	Techn. Performance	various	Technological properties relevant for storage - Efficiency, Power & energy density, cycle & calendar life time	
	Tech. Flexibility	Various	Ability to respond to fast-changing operation cond. And adoption of new market situation - Dependency on infrastructure - Power ramps - Modularity	
Environmental impacts	Damage to ecosystem	Y	Loss of various species in certain time and area	-No major changes, only wording issues and description of indicators
	Damage to Human health	Y	No. of diseases based on human health statistics	
	Damage to res. availability	$	Risk of running out of resources	
Society and policy /social aspects	Socio-economic performance	-	Direct and indirect numbers of employment possibilities	Several discussions and changes of “acceptance” as there are highly different opinions about this criterion
	Acceptance	-	Opinions related to energy systems by the local population	
	Regulation & policy	-	Economic incentive-based policy	

6.4 Summary of MCDA approach and realization

A summary of all selected criteria and their hierarchy for AHP regarding the overall research goal is given in Figure 6-6. Elicitation for AHP was developed within conducted interviews and realized in the second half of the survey described in chapter 5. Stakeholders had the possibility to conduct the survey in English or German. The first part of the AHP survey section offered a short introduction to AHP and provided links to further literature. Each criterion was briefly introduced with a short description. Participants had then to set a modulator on the point of their preferred prioritization within the pairwise comparisons. An example of a pairwise comparisons of three sub-criteria related to environmental impacts is given through a screenshot of the survey in Figure 6-7.

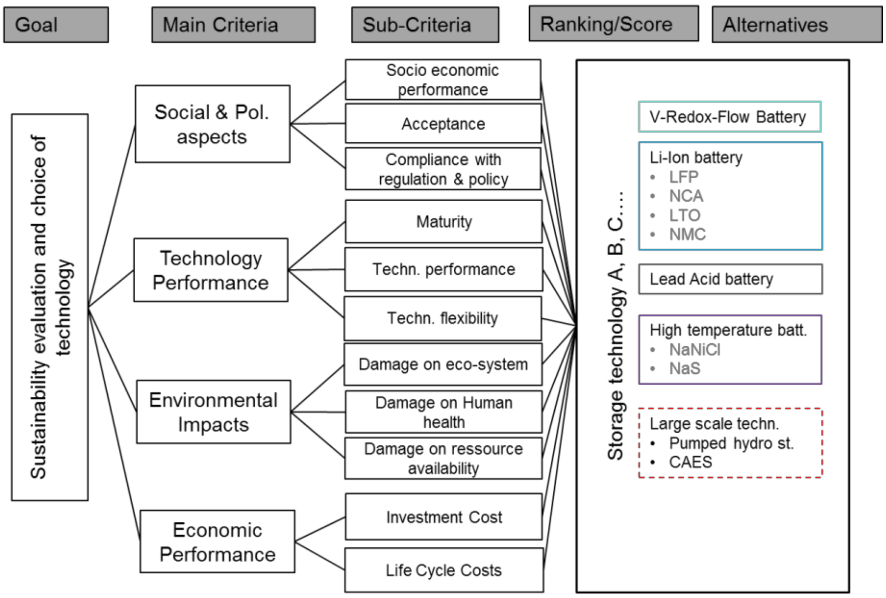
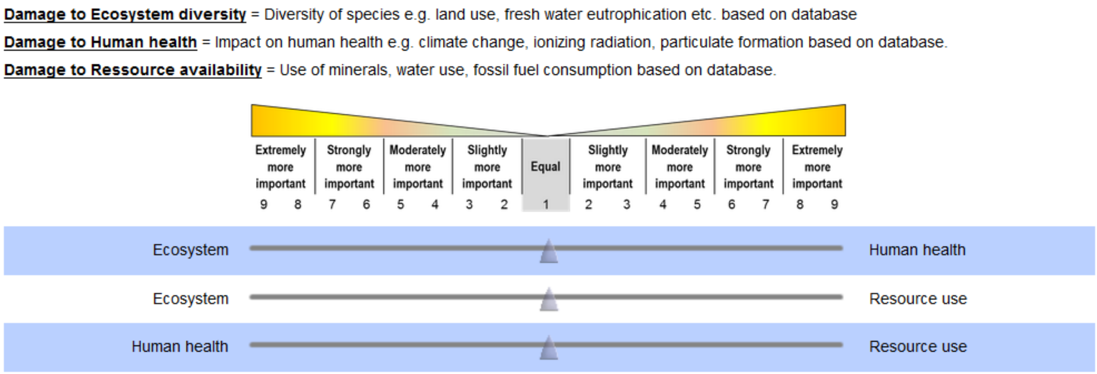


Figure 6-6: Overview of selected criteria and their hierarchy for MCDA as well a alternatives

The behind laying scale of the pairwise comparison was set from 1 to 17 and then converted into a suitable 1- 9 scale by calculating reciprocal values where, e.g. 9=1 for AHP or the reciprocal matrix. Most stakeholders liked the way of inquiry as it was easy and intuitive to follow. There were also concerns expressed that the easy way of setting preferences might lead to non-reflected prioritizations not representing the real participant opinions.



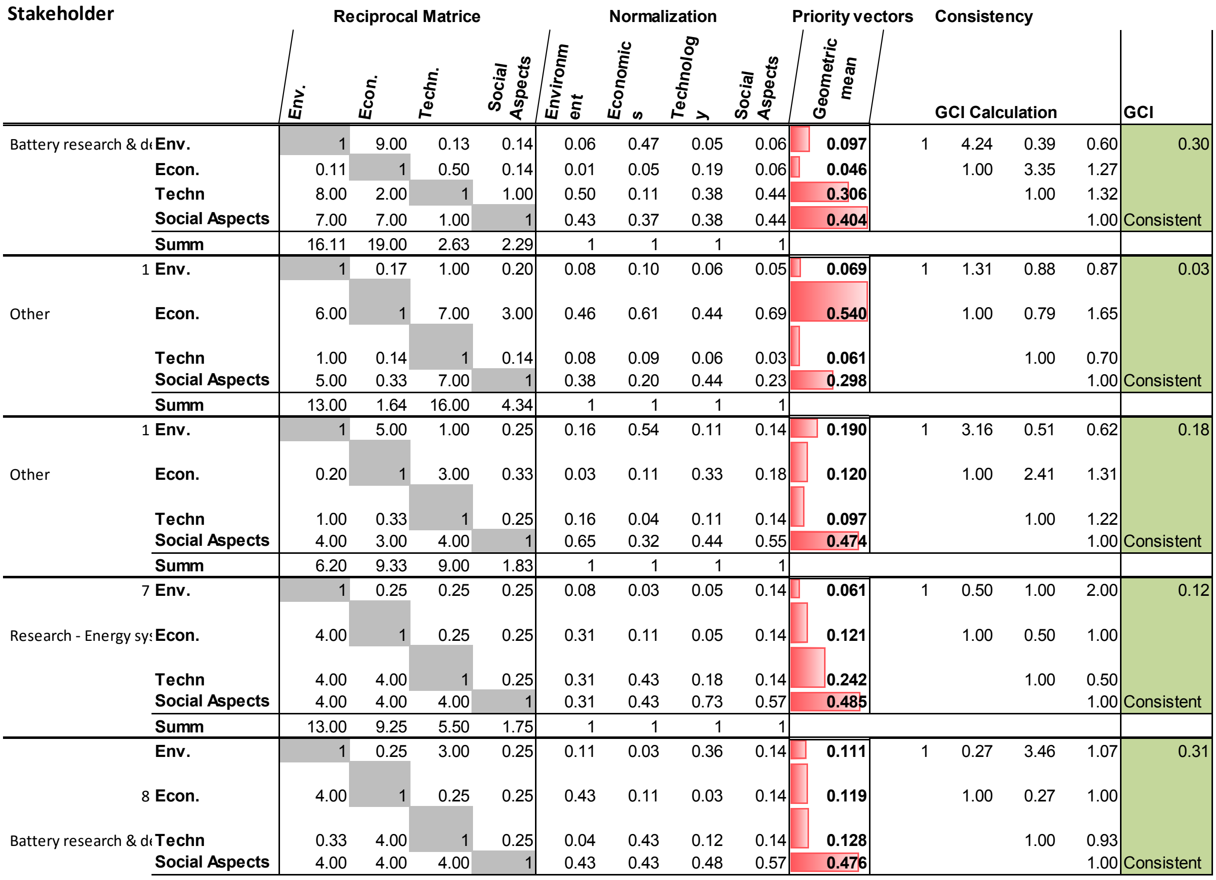
Damage to Ecosystem diversity = Diversity of species e.g. land use, fresh water eutrophication etc. based on database

Damage to Human health = Impact on human health e.g. climate change, ionizing radiation, particulate formation based on database.

Damage to Ressource availability = Use of minerals, water use, fossil fuel consumption based on database.

Figure 6-7: Screenshot of a pairwise comparison within AHP in the survey

Figure 6-8 provides a screenshot of the behind laying excel-VBA calculation for one set of criteria and four participants. The inputs in the form of comparisons from the stakeholders that participated in the survey were translated into the reciprocal matrices required for AHP to calculate the row geometric mean method (final weights are indicated by the red bars). In this case, the first participant is very concerned about the social impacts and the technology performance, whereas the second one perceives economic performance as the most crucial factor for technology selection. The green field indicates that the prioritization of this stakeholder can be considered as consistent as explained before (GCI=0.35 for n=4). This procedure was repeated for all chosen sub-criteria sets and stakeholders.



Stakeholder		Reciprocal Matrice				Normalization				Priority vectors	Consistency				
		Env.	Econ.	Techn.	Social Aspects	Environment	Economics	Technology	Social Aspects	Geometric mean	GCI Calculation				GCI
Battery research & de	**Env.**	1	9.00	0.13	0.14	0.06	0.47	0.05	0.06	**0.097**	1	4.24	0.39	0.60	0.30
	Econ.	0.11	1	0.50	0.14	0.01	0.05	0.19	0.06	**0.046**		1.00	3.35	1.27	
	Techn	8.00	2.00	1	1.00	0.50	0.11	0.38	0.44	**0.306**			1.00	1.32	
	Social Aspects	7.00	7.00	1.00	1	0.43	0.37	0.38	0.44	**0.404**				1.00	Consistent
	Summ	16.11	19.00	2.63	2.29	1	1	1	1						
1	**Env.**	1	0.17	1.00	0.20	0.08	0.10	0.06	0.05	**0.069**	1	1.31	0.88	0.87	0.03
Other	**Econ.**	6.00	1	7.00	3.00	0.46	0.61	0.44	0.69	**0.540**		1.00	0.79	1.65	
	Techn	1.00	0.14	1	0.14	0.08	0.09	0.06	0.03	**0.061**			1.00	0.70	
	Social Aspects	5.00	0.33	7.00	1	0.38	0.20	0.44	0.23	**0.298**				1.00	Consistent
	Summ	13.00	1.64	16.00	4.34	1	1	1	1						
1	**Env.**	1	5.00	1.00	0.25	0.16	0.54	0.11	0.14	**0.190**	1	3.16	0.51	0.62	0.18
Other	**Econ.**	0.20	1	3.00	0.33	0.03	0.11	0.33	0.18	**0.120**		1.00	2.41	1.31	
	Techn	1.00	0.33	1	0.25	0.16	0.04	0.11	0.14	**0.097**			1.00	1.22	
	Social Aspects	4.00	3.00	4.00	1	0.65	0.32	0.44	0.55	**0.474**				1.00	Consistent
	Summ	6.20	9.33	9.00	1.83	1	1	1	1						
7	**Env.**	1	0.25	0.25	0.25	0.08	0.03	0.05	0.14	**0.061**	1	0.50	1.00	2.00	0.12
Research - Energy sys	**Econ.**	4.00	1	0.25	0.25	0.31	0.11	0.05	0.14	**0.121**		1.00	0.50	1.00	
	Techn	4.00	4.00	1	0.25	0.31	0.43	0.18	0.14	**0.242**			1.00	0.50	
	Social Aspects	4.00	4.00	4.00	1	0.31	0.43	0.73	0.57	**0.485**				1.00	Consistent
	Summ	13.00	9.25	5.50	1.75	1	1	1	1						
	Env.	1	0.25	3.00	0.25	0.11	0.03	0.36	0.14	**0.111**	1	0.27	3.46	1.07	0.31
8	**Econ.**	4.00	1	0.25	0.25	0.43	0.11	0.03	0.14	**0.119**		1.00	0.27	1.00	
Battery research & de	**Techn**	0.33	4.00	1	0.25	0.04	0.43	0.12	0.14	**0.128**			1.00	0.93	
	Social Aspects	4.00	4.00	4.00	1	0.43	0.43	0.48	0.57	**0.476**				1.00	Consistent

Figure 6-8: Example of an AHP reciprocal matrix, normalization, priority vectors and consistency check for 5 participants

7 Technology evaluation

The choice of sufficient criteria is an integral part of the first step in the entire MCDA model. It is necessary to link the MCDA model with technology characteristics and potential application fields to provide insights into the performance of technology related to actor expectations towards an ideal configuration of storage technologies as indicated in Figure 7-1. The first sections are related to technological and societal criteria which are handled statically due to the scarce of application related data (grey fields not linked to application fields). In the second half of the chapter, a way to link technology evaluation with real-world application conditions is presented. This is done by the use of specific energy storage use cases and by calculating the impact of specific technologies (blue fields).

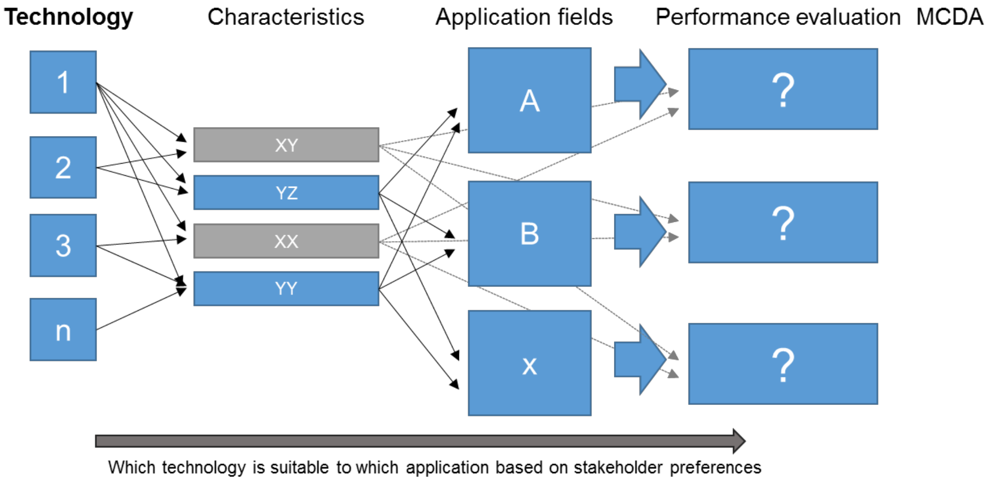


Figure 7-1: Schematic of procedure for technology evaluation for MCDA

Such use cases are required for a set of methods from system analysis; namely life cycle assessment, investment and life cycle cost calculation. Most of these application cases are taken from literature, whereas a new one is generated for a decentralized hybrid microgrid case, which also serves as a reference case. The last chapter provides a short discussion about the choice of indicators in this work and gives a brief insight to the results of other works to provide a more extensive picture of the challenges associated with the choice, definition, and quantification of these. Additionally, sensitivities are analyzed and discussed for the reference case.

7.1 Energy storage database

An energy storage database (Batt-DB) containing up-to-date techno-economic data from industry, literature and scientific reports for all types of secondary batteries [90], [189] is developed as a base for technology evaluation. This database includes over 5,000 data points for 12 different battery types including the years 1999 to 2016. The database is continuously updated and provides data about efficiency grades, energy and power densities, specific cost, cycle and calendar life time and others. An overview of the values obtained from Batt-DB and used for technology evaluation is given in Table 7-1, which also includes data for PHS and CAES. The high amount of available data makes it possible to gather bandwidths of different energy storage performance properties. Only datasets starting from 2014 have been used for this evaluation.

Table 7-1: Key performance parameters of the assessed batteries using upper quartiles, median and lower quartile values using values from [89], [90] and [91]; assumptions for compressed air energy storage (CAES) are based on the work of [92], [93], [94], [95] and for PHS [96], [92], [97], [98].

		Assessed Battery technologies										Other technologies	
Component	**Unit**	**Range**	**VRLA**	**LTO**	**LFP**	**LMO**	**NMC**	**NCA**	**NaNiCl**	**VRFB**	**NaS**	**PHS**	**CAES**
Cost	€/kWh	25 q	169	600	289	153	192	172	86	129		500	700
		median	230	900	309	238	318	213	220	458		750	850
		75 q	320	1200	315	564	554	355	403	860		1000	1000
Cycle life time @ DoD 80 %	-	25 q	300	4500	1750	1000	1000	1250	1000	9000		-	-
		median	1400	8000	5000	1500	4000	3000	3000	10000		-	-
		75 q	1600	9750	5325	5000	4875	5125	6250	13250		-	-
Efficiency	% DC-DC	25 q	63	81	83	85	83	90	84.25	65		65	45
		median	76.5	90	96	94	93.8	91.55	86	75		75	54
		75 q	90	94.5	96.5	98.25	97.275	93.1	91.25	85		80	70
Calendric	a	25 q	10	10	7.5	5	5	10	10	6.25		39	23.7
		median	18	17.5	15	10	10	10	14	15		40	35
		75 q	20	25	20	15	15	15	14.8	20		60	40
O&M	€/kW y	25 q	4.3	11	17	20	20	20	12.4	17.7		3	2
		median	16.9	25	25	25	20	25	20.9	40		15	6
		75 q	37.4	33.8	31.3	30	30	30	44.8	50.5		18	19
Investment cost per kW												623	517
												750	850
												1975	1000

Older data sets are only used in cases where no actual data was available for a technology or a specific parameter. This is especially the case for NaS and Vanadium Redox Flow batteries.

7.2 Evaluation of technology criteria

There is a high magnitude of technological criteria available in the literature available for energy storage systems (see chapter 2.8.3). The ones selected in the frame of this work in cooperation with stakeholders will be presented in detail in the following. They are viewed as general characteristics relevant for all applications fields. Most of the required battery performance parameters (cycle- and calendric life, charge/discharge efficiency, and costs, etc.) for all batteries are derived from the Batt-DB.

7.2.1 Technology performance

Technology performance is related to common technical properties of energy storage technologies highlighted in literature as [71], [59] and [68]. This indicator consists of five energy technology indicators as follows; Firstly, the efficiency which refers to how energy can be converted through an energy source by measuring by the ratio of output to input energy. The second and third indicator for technology performance is represented by the calendric and cyclic life time. Both factors are seen as critical for the economic and environmental performance [190]. Finally, energy and power density are also included as battery technologies have highly varying characteristics in this regard. The weighting of subcategories was carried out by experts in the frame of the survey in the continuum of 1 t o10 (low, high and very important, see chapter 5.5.2).

The attributed scores to different energy storage technology characteristics are indicated in Table 7-2. Obtained values are normalized to derive weights. Most stakeholders consider the factor of calendric and cycle life time as most important for stationary energy storage. Energy density is ranked last as there are not that strong limitations regarding size and weight of a storage unit. Power density and efficiency are considered as almost equally important in total. The low degree of variance indicates that there is some consensus on the importance of these two aspects.

Table 7-2: Distribution of weights including variance based on survey results with n=50

	Calendar life time	**Cycles life time**	**Efficiency**	**Pow. density**	**Energy density**
Mean	8.64	8.60	7.38	6.88	4.72
Stdv.	1.45	1.44	1.98	2.19	2.38
Variance	2.08	2.11	3.9	4.8	5.6
Normalized	23.85%	23.74%	20.30%	18.99%	13.03%

It can be seen in Table 7-2 that technology properties can vary considerably. These variations are considered by including three different technology performance scenarios, which are simply named pessimistic (lower quartiles of technology values), base (median values) and optimistic (upper quartiles). Weights and technology performance values are used to calculate relative performance of each technology by the use of TOPSIS. The evaluation results from TOPSIS can be found in Table 7-3, where also the main impact factors are included regarding their positive or negative influence on overall scores. It has to be noticed that the values have to be seen in relation to each other where, e.g., the case for LFP where the optimistic case shows lower values as in the base case due to changes of all scores. PHS and CAES achieve the highest scores due to their high calendar and cycle life time (LTC and LTY) which are ranked the highest by actors in relation to the other parameters. VRLA scores the lowest due to its relatively low cycle life time (LTC), energy density (ED) and efficiency (EF).

Table 7-3: Different technology performance evaluation scenarios using different weight in TOPSIS, EF=Efficiency, ED=Energy Density; LTC=Cycle Life Time; LTY=Calendric Life time; PD=Power density

Technology	Pessimistic	Base	Optimistic	Pos.	Neg.
LFP	0.372	0.410	0.362	EF, LTC;PD	ED
LTO	0.288	0.357	0.328	EF, LTC, PD	ED
LMO	0.279	0.312	0.302	EF, ED	LTC
NCM	0.351	0.401	0.369	EF, ED	LTC
NCA	0.329	0.358	0.328	EF, ED	LTC
VRLA	0.171	0.226	0.228	LTY	LTC, ED, EF,
NaNiCl	0.249	0.283	0.271	ED, PD	LTC EF
VRF	0.226	0.291	0.283	LTC	PD, EFF, ED
NaS	0.244	0.325	0.291	ED	PD, EF
PHS	0.759	0.738	0.771	LTC, LTY	EF, ED
CAES	0.617	0.692	0.613	LTC, LTY	EF, ED

7.2.2 Technology flexibility

The criterion of technology flexibility represents the ability of a technology to be built up without restrictions on any geographical location, to provide a high magnitude of different services and to adapt to new market situations. Restrictions can be based on topographic aspects as, e.g., the need for a height difference and the need for additional infrastructure as water supply for PHS or a gas pipeline system for CAES. The ability to provide different services is determined by a technologies response time [88], [92]. These can vary in dependence of the technology from milliseconds up to several minutes or hours. Another critical factor is the modularity of a technology which allows increasing storage capacity or power retrospectively to adapt to new market situations in the face of a growing share of intermittent generation. This ability is influenced by the energy to power ratio (E/P) of energy storage technologies as this relation limits to a certain degree modularity.

The qualitative evaluation is based on literature and on a simple traffic light principle where points are attributed from 1- to 3 for each color (red=1/low, orange=2/moderate, green=3/good) whereas intermediate allocations are rewarded with 0.5 points. The results for flexibility evaluation are given in Table 7-4. It can be seen that CAES has in general fast response times but that switching operation modes form charging to generation may take up to an hour [92]. VRFB has received half a point more in the field of modularity as the technology has a highly flexible E/P ratio as power and capacity can be scaled independently from each other. NaS has a fixed ratio of 6 [191]. The latter is thus only rated with 2.5 points regarding its modularity. It has to be mentioned that response time of NaNiCl and NaS are only fast when batteries are in operation. Cold starts take up to several hours [191], both are thus rated half a point less in relation to other battery storage technologies. VRFB and Li-Ion are ranked the highest, followed by VRLA and high-temperature batteries. CAES and PHS have the lowest score in this category.

Table 7-4: Aspects of technology flexibility based on [92], [88] and [191]

Technology	Infrastructure	Topography	Modularity	Response time	Total	Norm.
PHS	Electricity grid,	height difference between upper & lower basin, water	Low	3min	7.0	**1.10**
CAES	Electricity grid Gas Pipeline	Porous rock, salt cavern required	Medium	3 to 10 min response 36 min storage to gen.	6.5	**1.00**
Li-Ion	Electricity grid	None	High	Seconds	12.0	**1.95**
VRFB	Electricity grid	None	High ++	Seconds	12.5	**2.00**
VRLA	Electricity grid	None	High	Seconds	12.0	**1.95**
NaS	Electricity grid	None	Med high	Seconds Hours*	11.0	**1.84**
NaNiCl	Electricity grid	None	High	Seconds Hours*	11.5	**1.89**

*in case of cold starts

7.2.3 Technology maturity

The criterion of technology maturity is a crucial factor for technology evaluation when it comes to investment decisions. On the one hand, technological innovation is a prerequisite for corporation growth, but on the other hand, companies also try, in various ways, to prevent change to maintain a stable state. The use of innovative technologies is usually associated with higher uncertainties and costs in relation to mature technologies. Companies usually inhibit a rational view in which management may be able to anticipate and control the risk of innovation to a certain degree. This is usually done by quantifying likely dangers (investment calculations, SWOT-analysis, etc.) as well as rewards and to weigh them to each other to justify anticipated costs and decisions [192]. Such situations of uncertainty may induce a company to reject the effort of innovation or at least allow them to continue in an isolated or critical reduced way. Somehow, they also might adopt innovation by compartmentalizing it or oscillating between support and resistance. This reaction can be considered conservatism which is implicitly embedded in every company leading to the ambivalence according to innovations [192]. Investment decisions are thus often in favor of established technologies [104]. It can be questioned if all arguments apply to every company type. Especially investment intensive and large industries as chemical, energy utilities or car manufacturers can be considered as more conservative regarding innovations. Less capital intensive industries tempt to adopt innovations faster, as it takes fewer resources to make an invention marketable.

There are several ways to measure the degree of maturity, e.g. by categorizing technology into different technology readiness levels [121] or others [8]. This work follows an approach with an orientation towards [104] using patents to determine the life cycle stage, which can also be considered as maturity degree of the considered technologies and installed unit data. Examples to determine the life stage of a technology through the use of patents are given in [193] or [194].

The latter was extended through [195] as depicted in Figure 7-2 which expresses the theoretical development of patenting activity. This activity can be measured by the number of patent applications over time (e.g., years). It is possible to distinguish 4 idealized phases within a technologies life cycle based on [195] and [194] as follows: I) an emerging phase of new technology initially with stable patent activity with an abrupt interruption by increasing activity (representing the end of development phase); II) a consolidation phase with decreasing growth of patent activity due to new focus on first experiences with new technology; III) a market penetration phase with strong growth of patent activities as new companies start to filing patents in the area; IV) a maturity phase where the peak can be seen as breakthrough where a technology reaches maturity. It has to be mentioned that patent applications may also follow the stages of hype cycles, more precisely the expectation phase. This might indicate rather a market reserve characteristic then real technology development [195]. It is assumed that patents mirror to a certain degree the changes of technological change. Such a "technology life cycle curve" can be plotted by patent applications over time. More information about technology life cycles can be found in [195], [194]. An overview about patents and the detailed results for single technologies can be found in Annex B.

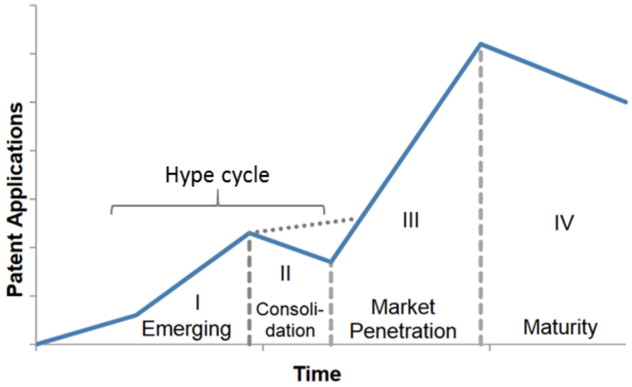


Figure 7-2: Amount of patent applications along different stages of a technological innovation life cycle [195], [194].

The patent search is carried out in Depatisnet by the use of the internal IKOFAX search language [196]. IKOFAX allowed the combination of relevant IPC main classes, country codes for priority countries and keywords for technology by Boolean operators to avoid wrong search results. Results of the search are then used to conduct a statistical analysis of bibliometric data. An example for Li-Ion batteries is given in Figure 7-3 (for more details see Annex B). It can be seen that the technology can be considered to be in a market penetration phase.

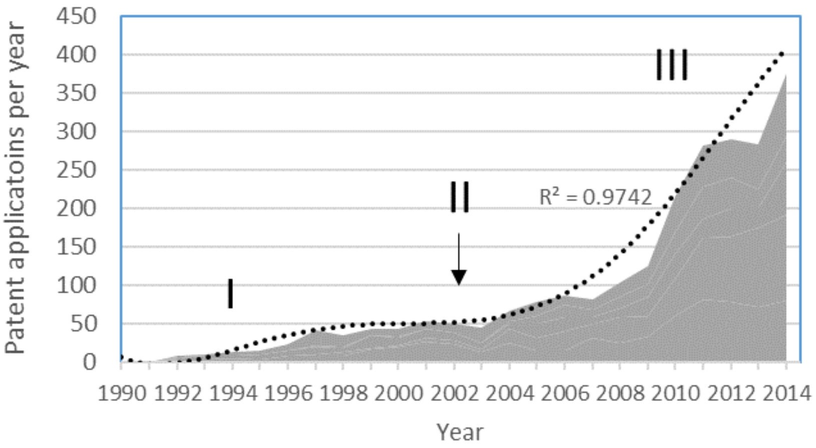


Figure 7-3: Innovation life cycle of Li-Ion battery systems (global patent data)

Data to calculate total installed capacities are taken from [65], [197]. It is not possible to distinguish different types of Li-Ion battery; they are thus handled as one technology. Additionally, other five maturity estimations from recent literature are presented in Table 7-5 and are used to verify own data. All literature data sets are normalized and, equal weights (10%) are used to calculate maturity levels. Own considerations on installed capacity and technology level are weighted slightly higher with 15% each. An optimistic case is included in calculating final technology scores which are not dependent on their maturity degree but only resulting performance.

PHS and VRLA represent the most mature technologies in relation to the other given options. Li-ion batteries have all the same score as it was not possible to break down installed capacity and patents into single electrode chemistries. NaS and NaNiCl have comparable scores whereas VRFB has the lowest maturity degree.

Table 7-5: Input data for maturity level of different technologies based on own calculations and literature [68], [198], [199], [200]

Technology	Inst. Cap in MWh	Techn. Life cycle	Av. From literature	Final score	Optimistic case
LFP	1484.6	3	8.53	**7.8**	**9.4**
LTO	1484.6	3	8.53	**7.8**	**9.4**
NCM	1484.6	3	8.53	**7.8**	**9.4**
NCA	1484.6	3	8.53	**7.8**	**9.4**
VRLA	181.2	4	10.00	**9.4**	**9.4**
NaNiCl	19.6	3	8.40	**7.7**	**9.4**
VRF	72.9	2	7.17	**6.4**	**9.4**
NaS	3670.0	3	8.54	**7.9**	**9.4**
PHS	140000.0	4	9.85	**10.0**	**10**
CAES	485.7	3	8.72	**7.1**	**9.4**

7.3 Social criteria related to electrochemical energy storage

The assessment of social factors is relatively new in the file of quantitative impact assessment, and identification or measurement of these is difficult due to a missing approved theory [201]. So far only a few studies exist on the evaluation of energy technology options in combination with social aspects and their operationalization as [104]. There is a common sense that social aspects represent a crucial factor for the success or failure of a distinctive technology [142] which has a long time been neglected by early policy programs. Social aspects are often addressed in literature, but there are only rarely definitions given [202]. The work of [201] provides several societal indicators for energy systems and technologies. Such factors are, e.g. availability of infrastructure for disposal and awareness level of risks. but all are related to technologies which have to a certain degree already penetrated markets as coal power steam, gas turbine combined cycle (CCGT).

Interviewed participants claimed that it is difficult to rate the social aspects of a new storage technology which is not or hardly available on markets. Most thought that it is very challenging to make this evaluation qualitatively based on the survey. This comes especially true for some technologies like battery storage where almost no literature and more importantly only limited knowledge about technology impacts is available (e.g., in the case of VRFB).

The social factors considered and discussed in the interviews will be explained in the following three sections starting with compliance with policy and regulation, socio-economic impacts and finally the perceived public acceptance of different (battery) storage technologies. Survey and interview results are supplemented by literature data where available.

7.3.1 Compliance with policy and regulation

The interviews have shown that participants see a lack of available market regulations for energy storage technologies. According to literature “compliance with policy and regulation” represents a factor of socio-political acceptance which can be seen as acceptance on the broadest level [202]. It can be defined as the influence of regulatory incentives to support certain directions of technological development. Such development can be cost-effectively steered by, e.g. the use of economic incentive-based policy. If there is no environmental policy available investments in environmentally friendly technology development, as well as diffusion, are likely to be less than they would be if socially desirable [203]. The indicator describes possible rules, specifications, policies or laws as obedience by a particular actor group related to technology development, diffusion, and investment. It represents a qualitative indicator that is rated by experts.

The work of [204] gives a more comprehensive picture of such regulations namely; 1) energy regulation and law as well as 2) construction, environmental and immission laws. The latter is concerned about frameworks related to recycling, water protection, and fire safety regulations. Participation on markets, access to the grid and billing are issues related to the first category. Aim of this work was to provide characterization sheets for different balancing technologies through an interdisciplinary approach and the inclusion of experts in the area. The results were then discussed and validated on a three-day workshop. Rating is based on a simple traffic light principle. An overview about the different distinctions for different rating possibilities and their meaning are given in Table 7-6 (red=low, yellow=moderate, green=very high).

Table 7-6: Evaluation scheme for regulation and policy issues related to different balancing technologies [204]

Color / indication	**Energy regulation and laws**	**Construction, environmental laws**
5	No need for action seen, framework available	No visible conflicts
4	Problems can be solved by small adjustments of existing laws	Problems can be solved by small adjustments of existing laws
3	Extensive changes in law required	Extensive changes in law required without lowering existing standards
2	Extensive changes in law required realization may not be possible	Extensive changes in law required with lowering existing standards
1	Operation of technology does not make sense under today’s legal framework	Operation of technology does not make sense under today’s legal framework

Participants of the survey were also asked to rate the level of perceived political support and the availability of adequate market and legal regulations for different technologies. Stakeholders argued that does not make sense to rate single battery chemistries as there is seen a gap in the general availability of a clear legal framework for these technologies. This gap is related to regulations regarding decentralized storage and market participation rules [204] and [P8ES], [P5U]. The latter participant also stated that mere regulation is not sufficient to integrate storage technologies into markets by, e.g. incentives. Furthermore, stakeholder [P6 Reg] also stated that this criterion is difficult to interpret as regulation does not automatically induce political willingness. The criterion is considered more as a process of continuous negotiation between regulation and policy, where the latter sets political targets which then must be discussed with the first if, e.g. adoption of current law seems to be necessary. The work of [205] provides a detailed qualitative analysis of experts opinions related to economic and institutional aspects of storage and is worth to be mentioned here.

Results for this criterion are combined with the evaluation conducted by [204] and own survey results where experts could rate the availability of regulations for each technology on a Likert scale from 1 to 5 (low, neutral and high). Final scores represent the sum of these values as indicated in Table 7-7. VRLA has the highest score among electrochemical storage technologies which is explainable through the well-established recycling system. The other technologies achieved all the same score as no distinction was made among them based on several stakeholder recommendations. PHS and CAES achieved the highest value regarding expert votes and available energy regulation and law. The first have to face high legal burdens before it can be implemented, which can be validated through Stakeholder [P8ES] experience with this technology.

Table 7-7: Resulting evaluation of socio-political aspects of different storage technologies based on own survey with n=69 and [204]

Technology	Energy regulation and laws*	Construction, environmental laws*	Own survey	Stdv.	Comment	Final score
LFP	3	3	2.9	1.04	Regulations missing (fire safety) – especially for large installations	**8.94**
LTO						**8.94**
NCM						**8.94**
NCA						**8.94**
VRLA	3	4	2.9	1.04	Regulations through the “Wasserhaushaltsgesetz” due to lead and sulfuric acid	**9.94**
NaNiCl	3	3	2.9	1.04	Regulations missing (fire safety) – especially for large installations	**8.94**
NaS	3	3	2.9	1.04		**8.94**
VRF	3	3	2.9	1.04	Concerns due to hazards & water protection	**8.94**
PHS	4	2	3	1.10	Environmental concerns	**9.01**
CAES	4	4	3.3	1.05	Comparable to CGCC	**11.28**

**Results from [204]*

7.3.2 Socio-economic impacts

Socio-economic performance is considered as a qualitative and a recapitulative criterion, roughly measurable [8], [111]. It can be expressed by a number of job creations, fair distribution of cost as well as benefits, social life and income generation. This makes it very difficult to rate new technologies under development regarding this aspect as there are often no statistics available [8]. An evaluation is furthermore challenging due to the missing consistent definition of this criterion. There is a comprehensive framework provided by [206] how to analyze the socio-economic effects in a quantitative way for the case of renewables. According to this study, value creation can be divided into different levels namely into impacts on a macro, meso and micro level including different variables (value added, welfare, employment, risk reduction, etc.). It was not possible to apply this rather complex framework in this work due to the high effort of data and time related to it.

Instead, expert opinions are obtained to at least collect qualitative notions about the socio-economic performance of new balancing technologies and especially battery storage. Survey participants could rate the perceived socio-economic value on a Likert scale of 1 to 5 (low, neutral – to high) of different balancing technologies related to job creation and fair distribution of costs and benefits caused by energy storage. Social factors named in the frame of the semi-structured interviews are strongly seen in the possibility of a higher autarchy for end-users resulting in financial and environmental benefits on a local level [P6Reg] and other aspects as lower emissions [P9Ac]. It was challenging for participants to rate this criterion due to its broad definition and the high number of variables that are involved for this criterion. Further discussion with participants has shown that this criterion seems to be more related to the general issue of technologies considered as decentral and those as central storage. It is thus not possible to distinguish socio-economic impacts for different battery storage technologies in this work. Technology ratings are thus set all to the same level as it would require more effort to provide robust values for this indicator. Survey results for socio-economic evaluation are given in Table 7-8.

Table 7-8: Resulting evaluation of socio-economic aspects regarding job creation and fair distribution of costs and benefits caused by energy storage of different storage technologies based on own survey with n=69 and [204]

Technology	**Own survey**	**Stdv.**	**Comments**	**Final score**
LFP	3.1	1.15	**None**	**Set to equal level**
LTO				
NCM				
NCA				
VRLA	3.1	1.15	**None**	
NaNiCl	3.1	1.15	**None**	
NaS	3.1	1.15	**None**	
VRF	3.1	1.15	**None**	
PHS	2.9	1.08	**None**	
CAES	2.9	1.08	**None**	

7.3.3 Perceived public acceptance of energy storage technologies

Social aspects related to energy storage can be broken down into three highly interdependent categories of overall societal acceptance namely: socio-political, community acceptance and market acceptance [202]. This interdependency is also named by interview participants who thought that it is difficult to distinguish these three levels of social acceptance. The indicator in this work is dedicated to community acceptance which represents a blurry notion of opinions related to energy systems by the local population regarding the hypothesized realization of the projects under review from the consumer point of view. This criterion is critical since the opinion of the population and of pressure groups may profoundly influence the amount of time needed to go ahead with and complete an energy-related project. This comes mainly true for energy storage technologies that directly interfere with the public, e.g. on a decentralized level for residual storage by visual impacts, perceived health and safety concerns, etc. [149]. RES as well as battery storage tends to happen closer to the end-users "backyard" and increases its visibility and brings environmental impacts closer to their residence [202]. This criterion is highly interesting and should be seen in contrast to more global notions on a socio-political or -economic level. Acceptance of technology on a community level refers to specific siting decisions and projects by mainly local stakeholder as local authorities and residents.

This level of acceptance is where the debate around "not in my backyard – NIMBY" unfolds. The NIMBY phenomena are something that cannot be rationally explained in this case. The major problem is that acceptance which is related to this phenomena is not really measurable [111]. Again, this criterion is not considered as a quantitative but a qualitative factor. Qualitative measures for various alternatives can be obtained via surveys carried out by the local community or city [8] as in the case of [100] or [99]. The semi-structured interviews in the frame of this work showed how difficult it is to handle this topic as participant's don´t see anything like a reasonable public acceptance of technologies as NaS or Vanadium Redox Flow batteries due to the missing knowledge of the public related to these technologies.

It is worth mentioning in this context that when people only know little about the technology they may depend on the trust in actors which are responsible for the development of technology [207]. The actors related to technology and their affective responses towards technology have thus a strong influence on society's perception of the risks or benefits of relevant technology. Estimating local acceptance is difficult as the case renewable energies have shown where authorities, investors, and companies thought that implementation is no problem as surveys on public acceptance of res revealed high levels of support for the technology. However, experience has shown that such results indicating public support, or support from essential stakeholders on different scales cannot be taken for granted [202]. Thus, results presented in the following should be taken as indicative.

The study of [204] also provided characterization sheets regarding the "societal acceptance" for different balancing technology using the same methodology as in the case of socio-political aspects. Rating is again based on a traffic light principle. An overview about the different distinctions for different rating possibilities and their meaning are given in Table 7-9 and are combined with own findings (red=low, yellow=moderate, green=very high).

Table 7-9: Evaluation scheme for regulation and policy issues related to different balancing technologies [204]

Color / indication	**Acceptance**
5	High acceptance, no local and national problems awaited
4	In general, high acceptance, little number of aspect that should be considered in implementation
3	Local and national acceptance not clear, further assessment required
2	Low acceptance, residents should be included in decision process
1	Not possible in Germany

Also in the frame of this work experts rated the perceived social acceptance level related to, e.g. impact on the landscape, perceived danger and of the considered technologies on a Likert scale from 1 to 5 (low, neutral and high). The issue of social acceptance was often related to the potential environmental or health impacts of toxic materials used in battery types as lead acid or vanadium redox flow batteries [P1RE]. The issue of the danger regarding explosions was also raised by stakeholders [P6Reg]. Experts also see potential acceptance problems when it comes to the acceptance of large storage units as PHS whereas battery storage is not seen as critical in relation [P8ES]. This impression was reinforced by [P9Ac] which stated:

> "*… and I think they are not that suspicious when it comes to batteries….*"

However, some Stakeholders see in general a deficit in the acceptance of large-scale solutions including large battery capacities. A significant issue named by participants in this context is the visibility of such large-scale technology solutions [P7Auto]. Results indicate common tendencies as [48] that energy storage is to a great extent socially accepted in relation to other components, e.g. construction of wind turbines, new transmission lines or power plants of the energy system. One exception is pumped hydro storage due to a perceived high impact on the landscape and related damage to the local environment. The option of building new flexible power plants (as in the case of CAES) is considered as unproblematic regarding local acceptance [P6Reg]. This is surprising as they also have a specific impact on the landscape and air quality. Stakeholders were asked to rate the perceived rate of public acceptance based on the impact on the landscape, and perceived danger (e.g., explosion, impact on landscape and toxicity). The final scores for public acceptance represent the sum of the results based on [204] and survey results as indicated in Table 7-10.

Table 7-10: Resulting general acceptance of different storage technologies based on own survey with n=69 and [204]

Technology	Public acceptance*	Own survey	Stdv.	Comments	Total Score
LFP **LTO** **NCM** **NCA**	4	3.7	0.94	Doubts about safety due to the danger of fire & explosion	**7.7**
VRLA	4	3.7	0.94	Well known but high amount of lead and sulfuric acid	**7.7**
NaNiCl	4	3.7	0.94		**7.7**
NaS		3.7	0.94	Concerns regarding the danger of fire	**7.7**
VRF	4	3.7	0.94	Concerns regarding large installations & leakage nearby population	**7.7**
PHS	2	2.8	1.23	High resistance of local residents	**4.8**
CAES	4	3	1.04	Comparable to CGCC	**7**

**Results from [204]*

It is worth to mention that technology evaluation itself can also be seen as an integrative part of acceptance as described in an acceptance behavior framework developed by [207]. This frameworks kernel is that acceptance out of a psychological view is based on expectations on social or environmental benefits, potential risks, and costs. These expectations are as already mentioned before linked to trust in actors related to technology. Every considered criterion used to evaluate technology provides new knowledge which itself might lead to higher acceptance or the contrary. An example is given by [208] where people had more knowledge about hydrogen as a fuel with safety risks, had a lower positive attitude to use it. Notions about the related environmental benefits through hydrogen were high which has led to a higher willingness to use it. The combination of both factors where perceived environmental benefits where higher then safety concerns have led to a positive effect on attitude and willingness to use [207]. Such effects may be based on the preliminary evaluation of technology acceptance have to be considered for result interpretation.

7.4 Evaluation model for environmental and economic criteria

It is necessary to develop a model that allows an evaluation of energy storage technology properties under different application conditions in a quantitative way. Operation conditions have a strong influence on, e.g. necessary maintenance efforts as well as potential replacement investments and thus on the total Investment, LCC as well as LCA results. This becomes especially true for most battery technologies which have a cycle or calendrical endurance limit [209]. The interrelation of cycles, DoD and cost, was an aspect of major concern expressed by experts in the conducted interviews (see section 5.5.3). The model thus includes an optimization for the proper dimensioning of batteries regarding cycle life time and DoD relation in economic terms. Additionally, cell cost degression effects are included to draw cost reduction in case of battery exchangement properly.

Involvement of stakeholders helped to choose and define realistic application scenarios for this purpose. The resulting operation profiles and future price developments for different application cases serve as a base for modeling. Based on averaged operation data an economic optimization of the battery storage system's nominal capacity is done, providing the base for the following, investment cost calculus, life cycle costing (LCC) and LCA calculation. The framework of the entire application related assessment process is depicted in Figure 7-4.

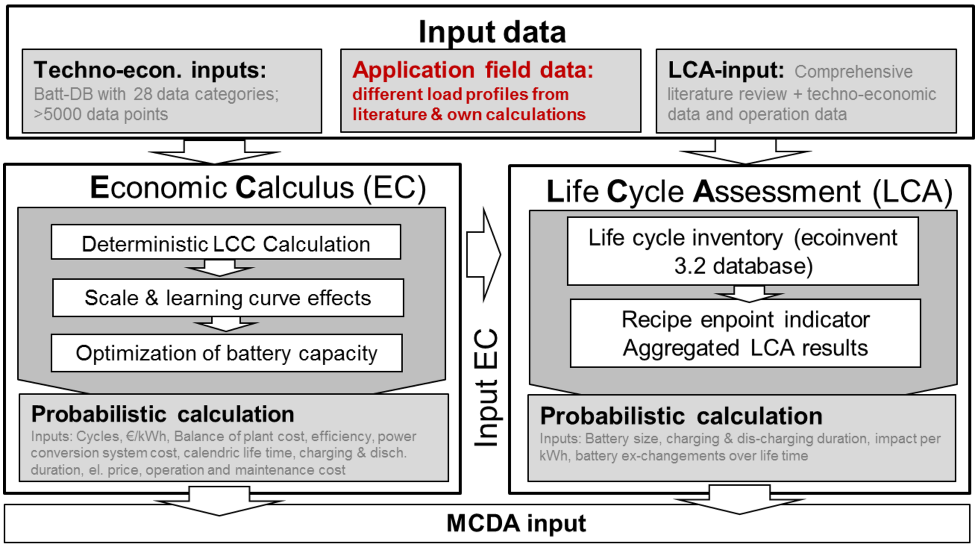


Figure 7-4: LCA and LCC model for battery storage evaluation

There are simplified approaches available in the literature that allow an evaluation of energy storage technologies by defining average daily cycles of storage with predefined capacities over a given project life time which is in this case 20 years. A good overview of such different business areas is given in [210] and [211]. The application of such generic use cases implies a simplification of the real potential requirements associated with energy storage. It was furthermore emphasized by stakeholders that new system concepts should be considered for battery storage [P5U]. Such concepts have to include PV, DSM, and storage units in a sense that the entire system becomes economic and environmentally viable. Examples of such systems are decentralized hybrid energy systems (HMGS). There are no representative load profiles for such a case available in the literature, making it necessary to generate such profiles firstly. The modeling of such a system requires a more sophisticated optimization-based model as it inhibits a higher degree of complexity.

Two different approaches are thus considered to provide a comprehensive picture of technology performance in combination with MCDA. The first approach is based on predefined conditions from literature whereas the second is based on a decentralized hybrid microgrid optimization model to generate such a load profile. Both approaches have been published in the context of this work and are thus only explained briefly in the following two subchapters [89] and [212].

7.4.1 Grid application cases from literature

The approach is based on standardized (yearly) cycles for different application fields and technology parameters as well as different dynamic integration scenarios which will be explained in the following. Stakeholders perceive batteries as suitable for applications on almost every level. One exception are long-term storage applications up to weeks. The following representative application fields were chosen based on the survey and semi-structured interviews in chapter 5 for assessment summarizing data from [65], [211]:

- Primary regulation (PR): Conjunction of measures for short time reconciliation of supply and demand. Energy is stored and released within seconds to respond to sudden spikes caused by, e.g. the intermittent nature of RES and to avoid changes in grid frequency [27]. PR is a high-power application, but also requires some capacity reserves in both directions, why on average the battery is maintained at 50% SoC.
- Electric time shift (ETS): Electric time shift is also referred as ‘arbitrage.’ Energy is stored during periods of low electricity market prices and discharged during times of high prices. This can help to compensate fluctuations in electricity generation due to increasing shares of RES where high or negative price peaks might occur on spot markets. It represents the typical application field for large-scale energy storage technologies as pumped hydro storage or compressed air storage nowadays. Batteries can also be used in this application until a certain capacity and power output of about 100 MW and a rating of around 800 MWh [210].
- Renewables support: Energy is stored by RES (e.g., wind turbine) operators when producing excess electricity and dispatched during high demand times. Typical timespans are multiple hours resulting in a high E/P- ratio (focus on storage capacity, not power) [213]

An overview of the different application cases is given in Table 7-11. PHS and CAES are only considered in large-scale bulk storage in the frame of ETS to conduct arbitrage business. A simple one-factor model namely; random walk price model (RWP) [214] is used for price prediction for the purchased electricity during storage unit operation. The model was applied within a Monte Carlo simulation to capture potential long-term changes in electricity, CO_2-certificates, and natural gas spot market prices until 2040. Historic spot market prices for the stochastic simulation are based on [215] and include the years 2007 to 2015. The desired operation period for the entire energy storage system is assumed to be around 20 years for all applications [216], [210].

Table 7-11: Overview of used cases for the assessment. ORWP = Abbreviations of Application cases see above

Application	Power [MW]	Capacity [MWh]	Cycles p. day	Electr. cost [€/MWh]	Source of economic value creation	Service value [60] [USD/kW]	Location in electricity supply chain	Sources
ETS	100	600	2	RWP [a]	Arbitrage	67-335	Transmission & Distribution	[217], [215]
PR	1	1	34[b]	RWP[a]	voltage and frequency regulation	6-6845	Transmission & Distribution	[210], [218], [215]
RS	2	20	1.12	80[c]	Arbitrage	44-1750	Generation	[219], [220], [221]

[a] RWP = Random Walk Price mode – See Annex I
[b] Adopted to German market conditions, 34 small cycles with an average DoD of 5 %, equivalent to 1.7 full cycles per day
[c] Levelized cost of energy for onshore wind turbine with operation times about ~2000h/a

It is important to mention that only costs are reflected by this analysis, but that the application cases have different potential revenues (see Table 7-11). Thus, the LCC does not necessarily correspond with the economic viability, what must be considered when interpreting results. Additionally, other storage technologies like flywheels or hydrogen, which are not covered by this study, might also be promising for comparable application fields [2], [3].

7.4.2 Decentralized grid optimization model for load profile generation

New decentralized system concepts as smart grids offer entirely new business possibilities for scalable electrochemical energy storage [P5U] and [P7Auto]. Especially the use of storage within Hybrid Micro Grids Systems (HMGS) which form an element of the smart grid is seen as a promising application field for battery storage. The aim of decentralized integration of Renewable Energy (RE) within HMGS is to maximize the share of renewable electricity directly consumed by local users. HMGS can be described as clusters of small generators, loads and battery energy storage systems connected through a local electricity network, controlled by a power management system that optimizes power flows. Such systems allow to reduce energy losses in transmission and distribution [222] and to increase autarchy up to a certain degree. A major challenge of such grids is the fluctuating generation behavior of decentralized sources as photovoltaics and wind turbines which correlate only poorly with loads. Battery storage technologies allow to match intermittent generation with local demand and are thus seen as a crucial factor for a safe and reliable HMGS operation. The problem is that the composition of these concepts itself is in their infancy. A simplified scheme of a grid-connected HMGS is given in Figure 7-5.

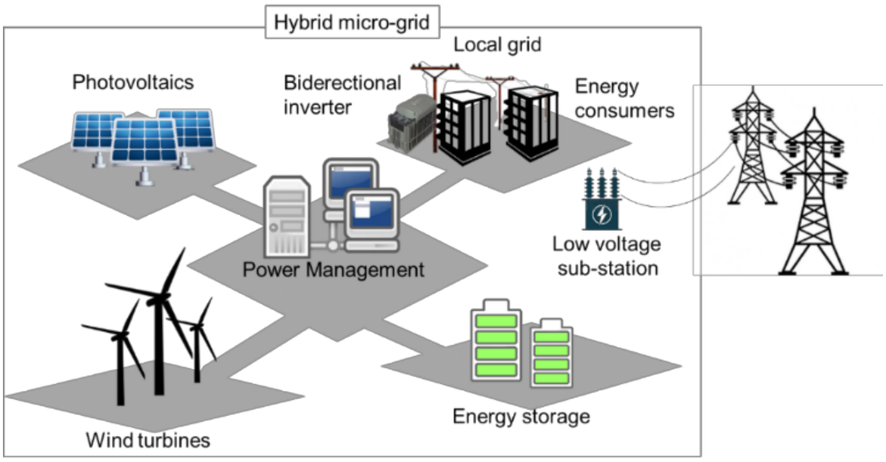


Figure 7-5: Simplified scheme of a grid-connected hybrid microgrid including photovoltaic, small wind turbines, battery storage and different loads (based on [223])

A micro-grid model including the Canonical Differential Evolutionary Particle Swarm Optimization (C-DEEPSO) algorithm is used to generate necessary parameters for the overall model used. HMGS modeling is realized via MATLAB® partially using a code initially developed by [224]. The model was reformulated for German conditions, including new boundaries, side conditions, a new optimization algorithm and techno-economic calculations. A aim of the HMGS optimization model is to increase the share of RES and to minimize the loss of power supply probability (LPSP) and the levelized cost of electricity (LCOE). This is achieved by finding the best composition of generation units and optimum battery operation mode in the HMGS. More details about the mathematical model can be found in [224] and [212] as they cannot be covered in detail here. The optimization results in the form of new time series, generation shares, and other operating characteristics are used to calculate the inputs required to conduct the MCDA. A scheme of the optimization model is given in Figure 7-6.

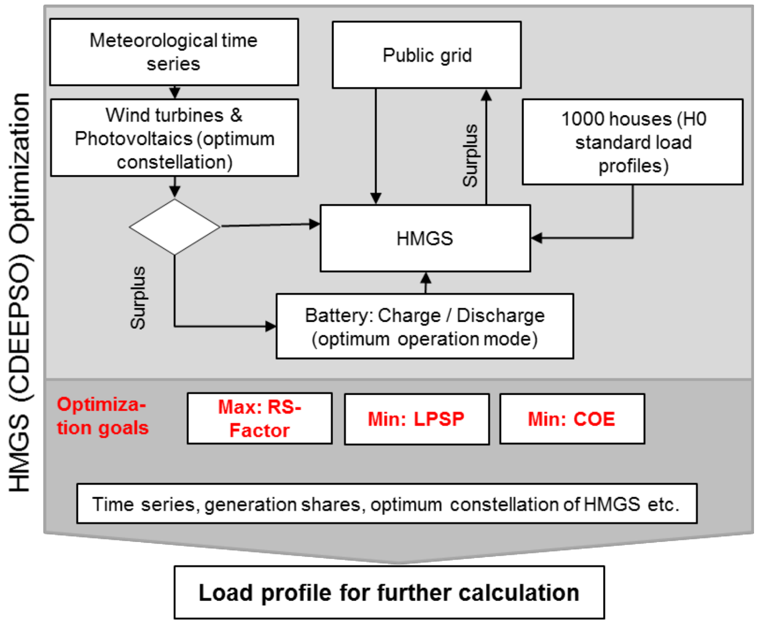


Figure 7-6: Simplified scheme of the used optimization model for HMGS and storage simulation

The original optimization is based on a PSO algorithm in combination with a linear scalarization technique for the treatment of the bi-objective problem wherein the objective functions have been combined into a single function. The share of RES is not directly integrated into optimization but is included as a boundary, which is set in this work to a goal share of 80%. C-DEEPSO is a new population-based optimization algorithm built upon swarm intelligence and differential evolutionary technique [225] and is used as a solving algorithm instead of PSO due to higher robustness of results [212]. More details about the C-DEEPSO algorithm and its properties can be found in [212] [225]. A generic battery [224] is used to provide a representative operation load profile for battery storage. Major assumptions for the HMGS optimization model are given in Table 7-12.

Table 7-12: Brief overview of major assumptions for HMGS optimization

	Values	**Comment**	**Source**
Size of community	1.000 residents	Average communities size in Germany	[226]
Electricity cost from grid	Without EEG-share & VAT resulting in 15 ct/kWh	No remuneration for feed in next grid level	
Load profiles	Normalized standard load profiles: H0 (33%), G1 (22%), G3 (44%)	Typical composition of load profiles for communities in Germany	[227], [228]
Meteorological data	Hourly values for irradiation, wind velocity, and monthly average temperatures	For south Germany (Black Forest)	[229], [230]
Wind turbines	P= 200 kW, 1687 €/kWp, d=30m, min v=2.7 m/s, rated speed=12.5 m/s max v=25 m/s, h=40; Operation time 1,720 to 2,230 h/a	Wind turbine type: WES30 from Windenergy solutions	[231]
PV modules	7.2 kWp each, 1,500€/kWp, Operation time 900 to 1260 h/a	Fixed modules, multi-Si panels	[224]
Storage capacity	1000kWh, 300 kW, DoD=80%, efficiency 85% and 220€/kWh and additional cost related to balance of plant (table section 7.6.1)	Generic battery, capacity depends on given boundaries for autarchy level (3 hours in this case)	[224], [228]

The resulting optimum HMGS constellation consists of a PV capacity of 1.739 kWp and includes eight wind turbines. An excerpt of the HMGS operation for one week in summer is given in Figure 7-7. The battery is charged when there is a surplus of RE and vice versa on the contrary case. Total battery capacity is higher than the net capacity of 1000 kWh due to a minimum SoC of 20 % and compensation of efficiency grade losses. It can be observed that wind and PV generation surpasses load (including battery charging) for an extended period (10 hours). These amounts of energy are fed back into the public grid and are not used within the HMGS.

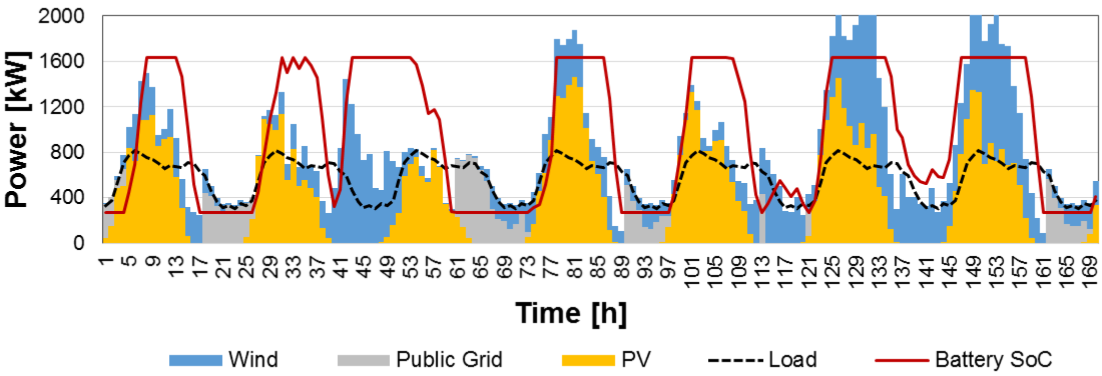


Figure 7-7: Excerpt of resulting battery operation over one week within an HMGS

No remuneration or restriction has been considered for the feed-in of surplus energy into the public grid. Including this could change overall LCOE with batteries and will be a task of future works. The contributions of the different RES to the battery charge is calculated based on hourly values for the specific wind- or PV- generated electricity surplus within the HMGS. LCOE for an HMGS with battery storage (18 to 27 €ct./kWh) are higher in average in relation to a system without storage (16 to 25 €ct/kWh), but RES share is increased by 7 to 15 %/a depending on the used meteorological data set. These costs do not represent the pure LCOE of battery storage. Though pure cost from RES in this application is depending on yearly operation hours resulting in a range of 9 to 16ct/kWh. Named bandwidths will be considered within a sensitivity analysis in the sections 7.6.4 and 7.7.3. All result bandwidths are given in Table 7-13.

Table 7-13: HMGS optimization results (bandwidths)

	Cycles	**Duration**	**Cost ct./kWh**	**Comment**
Average Load profile for MCS	**Cycles:** min 0.3 max, 1.40 (the latter is used as a central scenario)	0 to 3 h/d (the latter is used as a main scenario)	9, 13, 16 (depends on yearly operation hours of wind and PV)	Can vary extremely in dependence of chosen data set, maximum case assumed for HMGS

7.5 Consideration of uncertainties

A vast range of often contradictory values can be found in the literature for many battery parameters. Selecting or calculating one single value out of this value ranges can be problematic since it is always arbitrary and does not preserve any information about data uncertainty. This can be overcome by using probabilistic calculation methods, i.e., Monte-Carlo simulation, where a probability distribution is defined for every input variable [232]. The Monte-Carlo simulation (MCS) is seen as one way to include this aleatoric uncertainty into the MCDA. Due to the high number of datasets contained in the Batt-DB, ranges for most battery types can be obtained as the basis for MCS.

MCS is based on the law of large numbers, which implies that a value, based on a random experiment calculated command variable strives towards a real command value with an increasing number of simulations or drawings respectively [233]. This is especially helpful if the analysis of a real system is not or only partially possible [234]. The MCS is applied, e.g. by the variables efficiency, energy capacity, daily operation time, investment costs (cells, PCS, BOS), life time in years and cycles, and efficiency [235]. In general, such a simulation needs reference values and adequate probability functions. Distributions in this work are approximated by beta-Pert distributions. The beta-PERT distribution is comparable to a triangular distribution, requiring a minimum, most likely and maximum value, but the standard deviation is smaller [236] [237]. It is repeatedly applied in cost and LCA calculation for electrochemical energy storage systems [210] [235]. An overview of the MCS methodology is given in Figure 7-8. On the left side, various priorities are generated with a suitable distribution function and serve as an input to the MCDA model. The combination of different distributions results in a new distribution for Investment cost, LCA, and LCC.

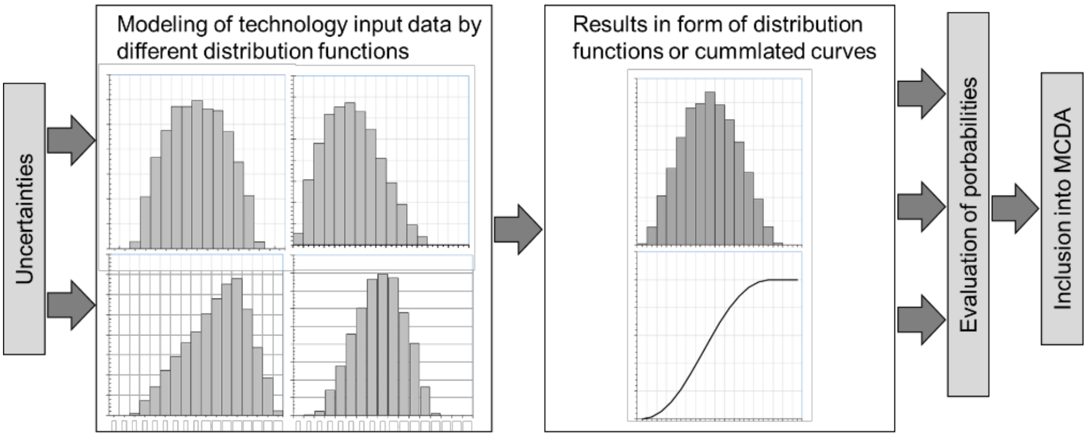


Figure 7-8: Example of MCS procedure

The model requires a proper number of simulations to achieve a distinctive accuracy (>1.000) [232]. Median values, upper and lower quartiles are used as an input for MCDA. Detailed information about probabilistic calculations of energy storage is given in [189].

7.6 Economic evaluation

There are several competing energy storage and other flexibility technologies under the frame of a liberalized European energy market leading to the question which technology is the most economically valuable alternative for a specific application field. This makes it difficult and only partially possible to compare different technologies with each other due to their suitability for different application fields, operation modes (amount of cycles) and development levels. The considered economic criteria are introduced briefly in the following:

Investment costs; represent the economic magnitude of the introduction of a technology. It includes all costs for all the project implementation phases relating to purchase of equipment, installation, construction of roads, buildings, engineering services, etc. [8] [117]. Investment costs are one of the most used indicators for energy planning [238]. Each storage technology has different cost structures and balances. An example is, e.g. the cost for battery storage which is mainly dominated by capacity (€/kWh) while CAES, and PHS are more dominated by power (€/kW) [48]

Cost (LCC) can be used for a systematic comparison of alternative project designs including total expenditures (initial investment, capital, replacement, operation, energy and disposal costs, etc.) over the whole economic life time of a product. LCC can provide insights to help society appropriately allocate limited financial resources to monetary optimize technical improvements. A central problem of LCC approaches for emerging technologies is that there is often only a limited amount of data available in combination with a wide value distribution and several calculation possibilities [239]. Some calculation procedures are non-discounted (e.g., cost comparison calculation) or discounted techniques (Internal Rate of Return – IRR or Net Present Value – NPV). All approaches have advantages and disadvantages as well as limitations and should be selected carefully regarding the scope and goal of the planned assessment.

Stakeholders agreed about the choice of the two criteria as they reflect different ways of evaluating potential investments from a company perspective. Investment costs play a higher role in short-term investment decisions. In contrary LCC plays a stronger role when it comes to mid- to long term investments. LCC and Investment costs are to a certain degree redundant when calculated but not regarding investment decision which is at the end always based on a company's preference [P2U], [P4U] and [P3RES].

7.6.1 Calculus of Investment and LCC

Initial investment costs are based on the rated power and capacity specific battery costs (C) in €/kWh [240] using the data of the Batt-DB. The battery life cycle costs are calculated using the annuity method in which present values are distributed in yearly equivalent series of cash flows over the entire life time of the storage unit. The quotient of the annuity and the total amount of energy stored and released by a technology represents the LCC of electricity storage or its probability respectively as indicated by Eq. 15.

$$LCC = \frac{C_{NPV} * \frac{(1+i)^T * i}{(1+i)^T - 1}}{P_{max} * t_j * \prod_{t=1}^{n} n_t * N_{cycles}} \qquad \textit{Equation 15}$$

C_{NPV} represents the net present value, which is just multiplied by an annuity factor where i represents a depreciation rate and t total amount of project life time. P_{max} is the maximum storage power, t_j total operation time over the period of one year, n_t is the sum of efficiency grades related to specific technology and finally N_{cycles} which indicates the total sum of cycles conducted within a year.

All storage technologies are scaled to the same effectively available capacity for comparability reasons within the investment and LCC calculation. This means that losses caused by different efficiency grades are compensated by adequately dimensioning each battery. Interest rates are based on the investors time value of money perception [241] to discount future expenditures to present values at a specific reference time point [242]. Depreciation is based on the assumptions of [210] where lower rates are assumed for smaller projects (6%) and higher ones for small-scale projects, e.g. in the frame of ETS where large utilities usually carry out the investment (8%).

Investment costs of all batteries are calculated in the same way. One exaptation is the VRFB which is dependent on the number of cells used in a stack, while capacity is depending on the volume of the tanks and the electrolyte amount and concentration [37]. The outcome of this fact is that VRFB is very suitable to store energy from a few hours up to several days [37]. This makes it difficult to estimate the cost of this battery type for different applications. Thus an exponential relation between the amount of required membrane and electrolyte was assumed based on [243] using the cost indicated in Table 7-1 as a starting point. This cell price was then multiplied with an energy to power relation dependent factor between 7 and 0.5 [190].

All considered cell types potentially have to be exchanged at least one time over the assumed period due to either non-sufficient calendric or cyclic life time. Learning curves were thus calculated to consider potential future cell-cost reductions in case of cell exchange. A learning rate of 82 % is calculated for Lithium based technologies resulting in high-cost reduction potentials in the years to come due to scale effects. The produced amount of LIB batteries in MWh/y and historical price data required for calculation were derived from [244], [245], [246]. Learning curves for other battery types were taken from [247], [248] and [249]. Development for NaNiCl and VRFB was assumed to be comparable with a rate of 87 % (average for battery technologies). Lead Acid PbA is the most mature electrochemical storage technology, which is used for a high quantity of power system applications since over 100 years [77], [5]. It is thus considered that cost reduction potentials have been actively exploited in the past resulting in a low future learning rate of 94 % [190]. An overview of learning curves and their calculation is given in Annex C.

Apart from battery cells, a stationary battery storage system requires electronics, infrastructure, and auxiliaries. The investment costs associated with the latter two are the so-called balance of system (BOS) and can contribute over 60 % to the total investment costs [250]. BOS include the cost for commissioning and installation and commissioning, structural and mechanical equipment such as protective enclosure, heating/ventilation/air conditioning (HVAC) and maintenance/auxiliary devices as well as communications and control equipment and can in total contribute up over 60 % of investment costs [250]. It is expected that BOS will follow a substantial learning curve through a portfolio of best practice in managing cost. This may lead to BOS cost reductions of around 40 % in the years to come [251] [252]. BOPs are poorly defined in the literature and that there are only a few reliable cost values available. Power electronics (PCS) cost in €/kW (AC-DC converters) is dependent on the size as was calculated by using cost digression exponents obtained from [253] and [254]. The assumed PCS costs were multiplied by a power dependent factor between 0.25 to 6. Inverter efficiency was estimated to be 0.95. All assumed costs are indicated in Table 7-14 [190]. Using this assumption has led to comparable cost shares in final results as reported by [253], [255]. For more information see Annex C.

All assumptions related to costs of CAES and PHS including major components are given in Table 7-15. More details about the cost structure of this technologies can be found in the sources given in the table. CAES requires further assumptions regarding fuel and consumption of natural gas and CO_2 emissions related to the combustion of fuel in the gas turbine. The CO_2 is traded form of CO_2-certificates in €/tCO_2 in the frame of the European emission trading system (ETS) and is together with natural gas a component of short-term marginal cost calculation.

Table 7-14: Specific battery cost assumptions typical cost shares are reported by [253], [255] and [190]

Type	**Cost €/kW**	**Av. cost share %**	**Comment**	**Source**
Contingency	83	-	Covers unforeseeable events	[252]
Installation	~125	~4		[252], [256], [243]
BMS+BBOS	273 - 475	12-40	Missing common definition	[252], [256]
Enclosure	~10	-	Dependent on technology	[252]
Inverter	-	10-20	Depends on scale effects	[253], [243]
Utility Intercon. equipment	~59	-	Can vary extremely	[252]
Battery	See Table 7-1	30-50	Technology-dependent	DatBat
Interconnection eq.	~59	~1	Dependent from location	[252]
Permitting	~50	-	Dependent of region	[256]

It was not possible to find reliable sources regarding de-construction and recycling of stationary battery systems, PHS and CAES. Thus, the waste treatment, disposal, and recycling of batteries is not considered here. This is apparently a simplification, since the end of life handling of different battery types and other storage technologies would vary significantly, but no established processes exist, and therefore no reliable data is available.

Table 7-15: Specific CAES and PHS cost assumptions

Type of cost	PHS	CAES	Source
BoP	~ 5 €/MWh	65-136-273 €/kWh	[257]
Fuel ratio (gas)	-	1.1 -1.16 kWh/kWh	[94], [93]
Fuel ratio (electricity)	-	0.67-0.7 kWh/kWh	[94], [93]
CO2 cost		0-26.6 €/tCO_2€	
Comments	Turbine & Pumps, Generator	Compressors, gas turbines, expander	

7.6.2 Calculation and economic optimization of cycle life time

Battery operation is optimized under economic aspects considering a minimum state of charge (SoC) which itself influences battery cycle life time [258], [235], [210]. A high Depth of Discharge - DoD (deep cycling) generally reduces battery cycle life, why batteries are often oversized in order to expand operation time. The aim is to minimize overall LCC by finding an optimal equilibrium between initial investment cost (battery oversizing) vs. replacement costs (reduced battery life) under given conditions for the different applications. It has to be mentioned that most battery types are not charged to 100 % or discharged to 0 % to avoid overcharge and discharge. Typical SoC ranges were thus assumed to be between 10 % to 95 % [259], [260]. A simple approximation of cycle life is applied in dependence of DoD using a approach formerly published in [261] under the named SoC restrictions. The methodology was already applied in [91] and [190]. Results for cycle life time calculation are given in Figure 7-9.

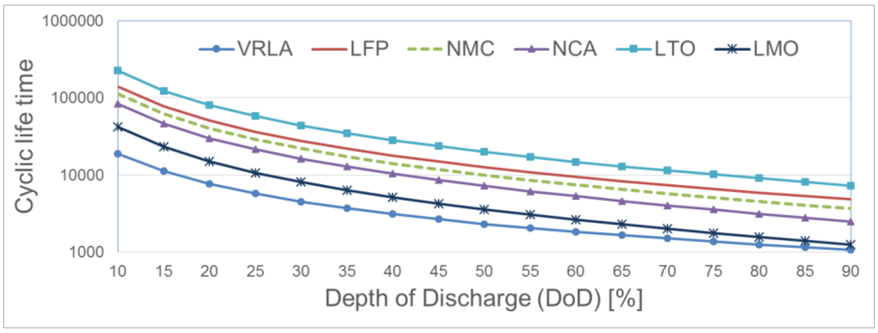


Figure 7-9:Calculation of DoD-Cycle relation [89]

An example for the optimization results for the LFP type battery in dependence of the minimum SoC and operation cycles per day (for, e.g. electric energy time shift -ETS) is given in Figure 7-10. LCC is found to be optimal for ETS at a min SoC of 23 % at an average of 730 cycles per year or 2 cycles per day (exemplary yellow line). Each "step" in the graph represents an exchange of cells (red line) which is highly dependent on daily cycles and min SoC. A lower SoC would lead to an earlier and potentially additional exchange of batteries which would result in higher overall cost. It can also be seen that in this specific case (fixed E/P relation), the optimization is highly dependent on the amount of cycles per day. A low number of cycles per year (i.e., 1 cycle per day) does not require a minimum SoC. The reason for this is that calendric life time (for LFP 10 years) dominates here as operation cycles do not surpass cyclic life time which leads to no further cost benefits through oversizing. Optimization results for all batteries are given in [89].

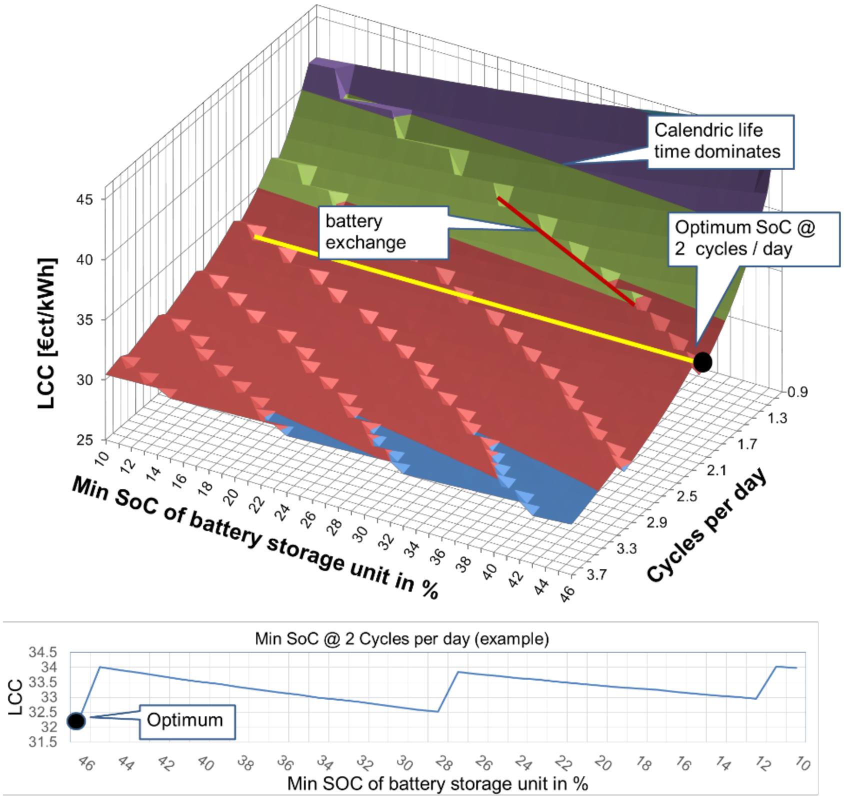


Figure 7-10: Sensitivity analysis of NCA min SoC in relation to operation cycles per year [190]

There was no sufficient data available to calculate cell degradation of VRFB. Thus a minimum state of charge of 20 % was assumed based on [262], [263] and [264]. It has to be mentioned that other

Literature reports that VRFB can also be operated in a SoC range between 5 % to 95 % as in the case of [265] – if this comes true cost may be overestimated in this work. For NaNiCl, ideal operation modes of the battery are reported to be between 30 % to 100 % [266]. In this work, a minimum SoC of 20 % was assumed as most information about cyclic life time of NaNiCl was only available at a DoD of 80 %. This represents a strong simplification in relation to the other battery types and calls for further research in this field. The model offers also the possibility to include changes in technology performance e.g. a certain increase of cycle life time after the exchange of battery cells. However, it is very difficult to estimate potential developments in this area. It is therefore simply assumed that a new cell generation would have a slightly higher cyclic life time of around 10 % over 20 years, resulting in a yearly increase of 0.5 % per year [89].

7.6.3 Resulting investment cost and LCC for specific applications

The simulation is carried out for 10.000 trials within a Monte Carlo simulation for each storage technology in every application field. Figure 7-11 provides an example of the distribution of results for investment and life-cycle cost for LFP used for primary regulation for the sake of the reader. The distribution function for investment cost is slightly left-skewed (0.141) with a kurtosis of 2.8 (indicating that variance comes more from the center) which is also the case for all other assessed technologies in this application. The results for 25%, 50%, and 75% quartiles are used as input for MCDA. Cost input for MCDA would be in this case 1,407 €/kWh, 1,442 €/kWh, and 1,493 €/kWh.

The distribution function of life cycle cost results is strongly left-skewed (4.5), and kurtosis is higher (33.3) in relation to investment cost due to high variance of tails (up to 1,000 €ct./kWh). This can be explained by a high target value within a triangular distribution regarding operation times per cycle which lead to decreasing LCC. Again, as in the case of investment costs 25%, 50%, and 75% quartiles are used as an input for MCDA. In this case, MCDA input values are 62.54 €ct./kWh 81 €ct./kWh and 124 €ct./kWh. A detailed overview of numeric MCS-LCC results is given in Annex D.

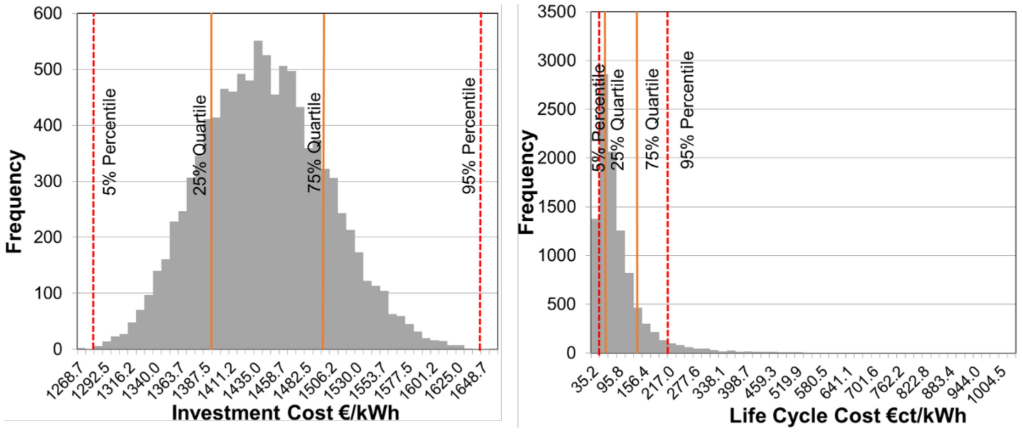


Figure 7-11: Example for MCS results regrading LFP investment and life cycle cost used for primary regulation

The initial investment costs obtained for the different battery types under the four considered application cases are displayed in Figure 7-12 in the form of box plots due to graphical reasons. The energy to power ratio (E/P) is also indicated for a better understanding of the results as this ratio highly affects initial investment costs. The box plots show the 5 % and 95 % percentiles, 25 % quartiles; median and 75 % quartiles and provide an idea of the uncertainties, and shape of the distribution function of results associated with the given calculations. The case of HMGS is separated from the other cases as it is based on a real load profile generated by an optimization model.

In the case of ETS and CAES and PHS are compared with other battery storage technologies whereas two lithium-ion batteries were excluded due to graphical issues. These battery types are included in all other comparisons. Investment costs correlate to a certain degree with LCC; they will thus be interpreted together. The life cycle costs including main cost shares for all considered application cases and technologies are displayed in Figure 7-13. Again, as in the case of investment costs, box plots show the result distribution and provide an idea of the uncertainties associated with the given calculations.

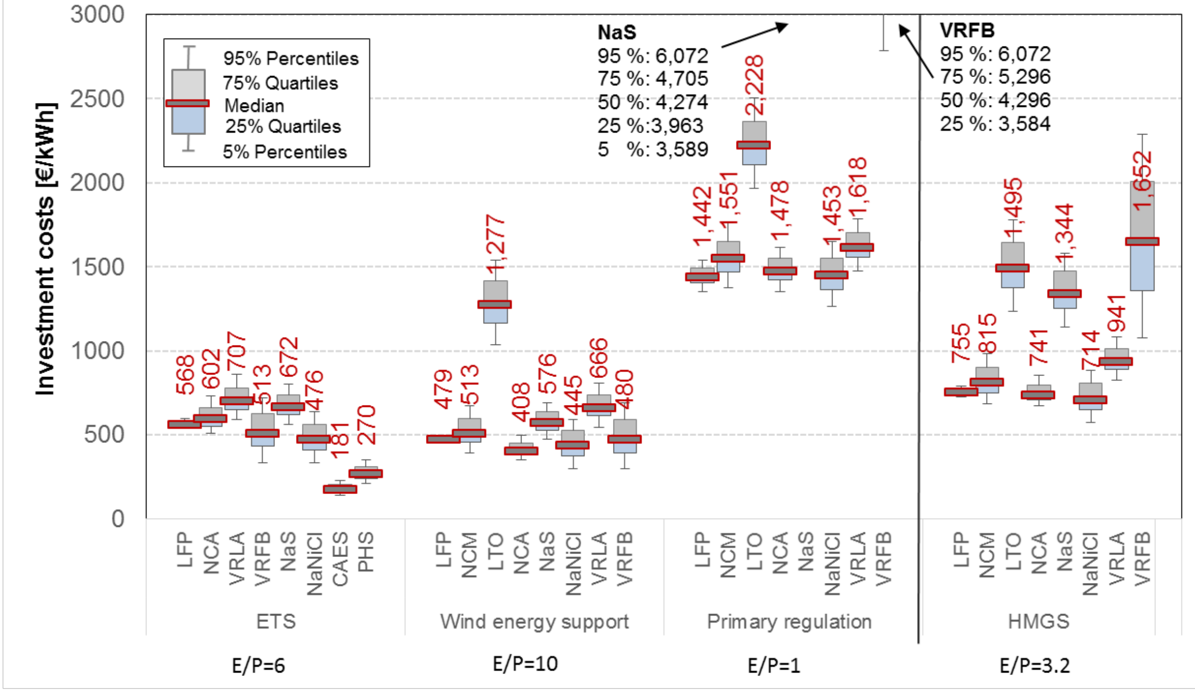


Figure 7-12: Resulting investment cost for all considered technologies and application cases

The investment cost and LCCs obtained per kWh of electricity provided vary strongly between the four considered application cases. While costs for ETS, RS, and HMGS are on a similar level, those for PR are significantly higher, as well as the corresponding uncertainties. The ranking of the different battery chemistries also changes from one application case to the other, highlighting the importance of a well-designed storage system optimized for the desired application. Especially the VRFB shows fundamentally different performances depending on the application case, as discussed in the following.

ETS: With an E/P ratio of 6, ETS is a low power application, what reduces investment costs for power electronics and BOS. The combination of a comparably high amount of cycles (use-intensive application) with relatively low initial investment costs gives the lowest LCC among the four application cases for all batteries. Highest costs are obtained for NaS and VRLA, due to comparatively low-efficiency grades. Cost related to VRLA results from a comparably low cycle life. In the end, none of the considered electrochemical energy storage technologies can compete against CAES and PHS. The latter represents the most economical energy storage technology up to date. CAES tend to have lower investment cost, but natural gas and CO_2 emission cost can represent a significant cost factor and may increase in the future.

Wind energy support (WES): The profile obtained for WES is comparable to that of ETS, though with slightly higher median costs for all technologies due to higher specific costs wind turbine generated electricity. Here, LTO has the highest cost among the group of LIBs due to its high initial investment cost. The LCC of VRLA are the highest in this application because of low expected price reductions and strong oversizing in combination with a low cycle life of this type of battery. The E/P ratio of 10 required by this application favors VRFB, which obtain costs comparable to those of LIBs, mainly due to the low initial investment cost of about 513 €/kWh.

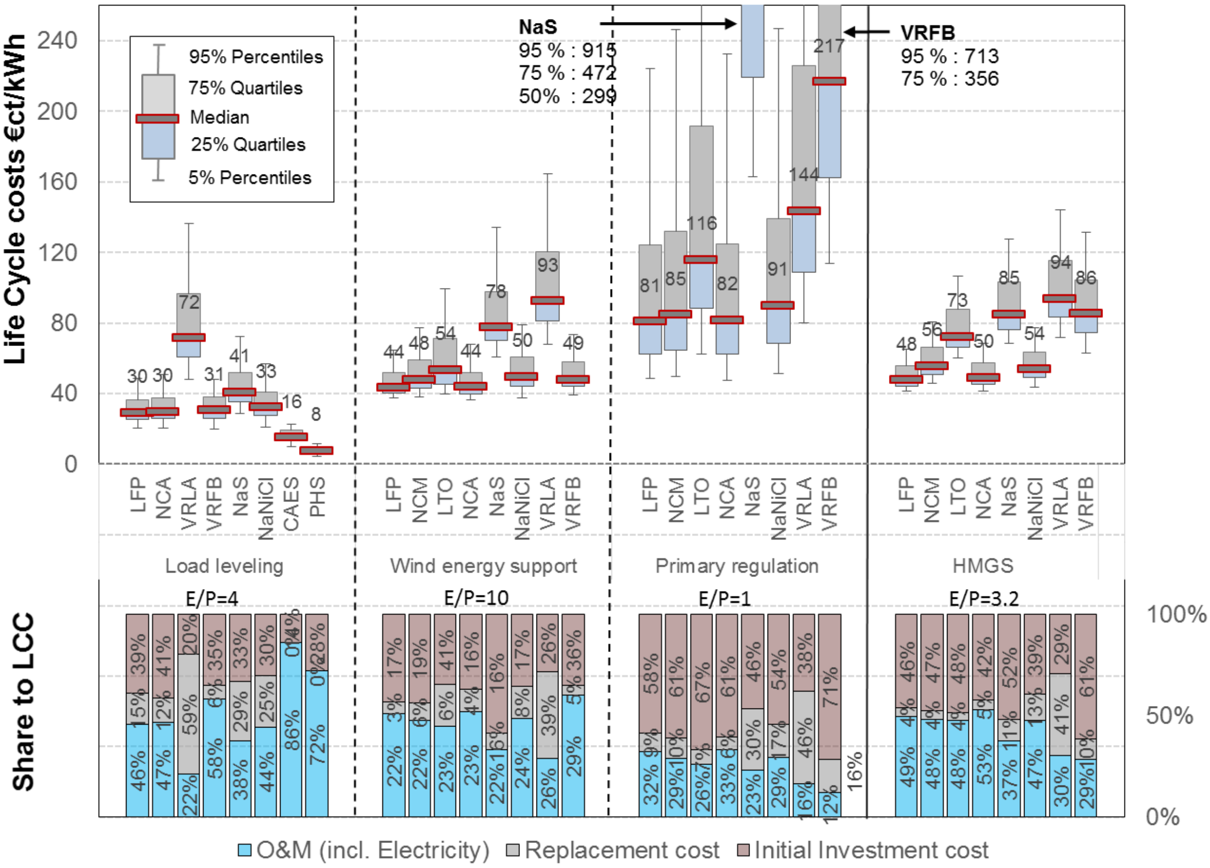


Figure 7-13: LCC results for all considered technologies and application cases including cost shares.

PR: This application is characterized by a high amount of small cycles per day in combination with a very high E/P ratio and comparably few total operation hours per year (~230 h/y). This leads to significantly higher investment costs for all battery types, especially for NaS with a median LCC of 2.99 €/kWh due to significantly oversizing (E/P=6). VRFB also shows relatively high cost in relation to other battery types. High LCC are obtained for all battery types, mainly due to low operation hours per year in this application. The combination of these factors also leads to comparably high uncertainty in the results (large LCC bandwidths). Nevertheless, PR has high potential revenues and is therefore considered an economically very interesting business case [60].

HMGS: The requirements for HMGS are characterized by a comparably low E/P size. The overall rise of average LCC in relation to WES can be explained by a higher cost for PV- and micro wind turbine generated electricity. VRLA show the highest LCC for this application, mainly due to its low-efficiency grades in combination with high electricity costs. Again, the cost for NaS and VRFB are also relatively high due to an unfavorable E/P ratio of 3.33, resulting in higher initial investment costs. Here only battery storage is evaluated, whereas in the optimization model total HMGS is evaluated where battery cost has only a particular impact on total cost.

7.6.4 LCC - sensitivity analysis for HMGS

Figure 7-14 provides an overview of the parameter sensitivity in LCC calculation. LFP has been used as a reference technology together with the HMGS use case. Median values of depicted values are taken and varied within a bandwidth of -20% to 20%. Negative changes of single parameters are given in light grey and positive ones in dark grey. Result variation is depicted around the median of 48 ct/kWh. It can be seen that e.g., decreasing cycle life time leads to an increase of LCC and vice versa in the case in case of cell cost. The impact of DC-DC efficiency is the highest in relation to the other parameters due to high electricity costs, whereas calendar life time has no impact as cycle life time is more relevant. Efficiency grade is 96 % for LFP, 100% thus represents the maximum positive change with +4.2 % (even if unrealistic). A maximum discharge time of 3 hours is used for calculation. Thus only negative changes are conducted. It becomes clear that LCC is highly dependent on HMGS operation conditions.

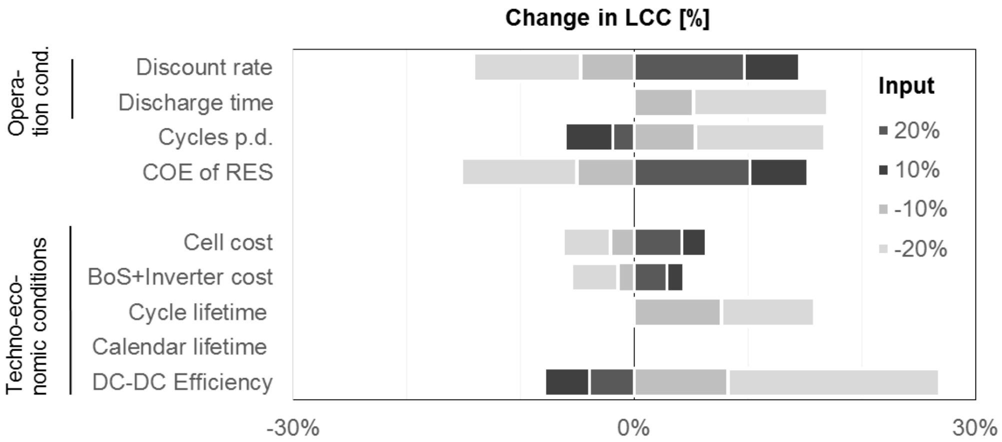


Figure 7-14: Sensitivity of LCC to different parameters of battery operation and properties (inspired by [5])

A detailed overview about the interrelation of varying operation parameters on overall LCC is given in Figure 7-15 A and B where the high dependency of the LCC on the daily charge duration and daily cycles can be observed in the first. These influence battery exchange rates and yearly operation hours strongly, why the proper definition of the application case is a critical issue. Other important factors are the electricity costs and efficiency grades, which directly affect operation costs (Figure 7-15 B). A comprehensive sensitivity analysis of different investment cost, operation conditions and technology properties for ETS, WES and PR is given [190] and is not provided in the frame of this work.

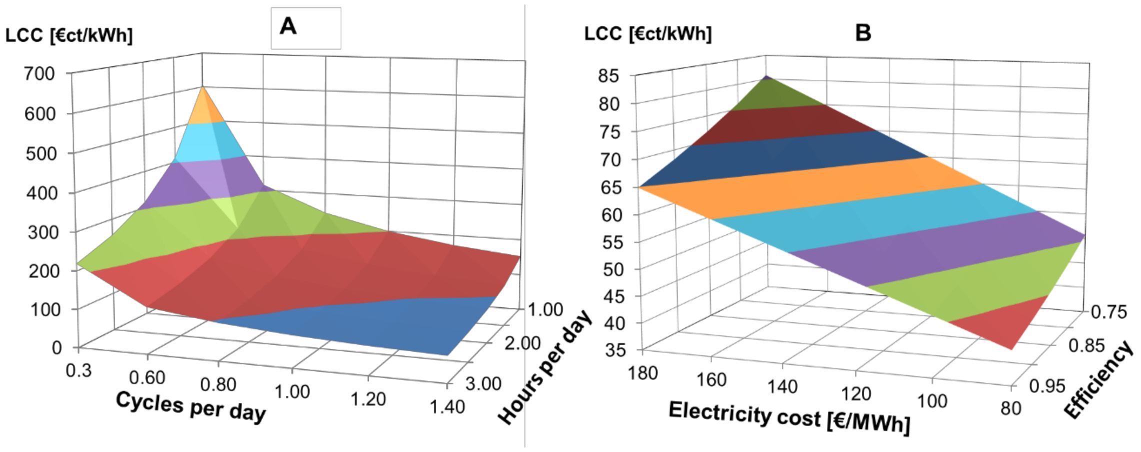


Figure 7-15: LCC sensitivity analysis of HMGS with LFP for A) operation conditions including the number of cycles and charging time per cycle B) Influence of efficiency and purchased electricity.

7.7 Quantification of environmental criteria

Life Cycle Assessment (LCA) is used to calculate potential environmental impacts of technology over its entire life time. It is a standardized approach [159] and [160] that documents a product's or product system's environmental impact over the complete life cycle. This includes the mining and refining of primary material, the production phase, energy consumption, emissions and maintenance efforts over the entire use phase, as well as repercussions from the treatment at the product's end of life. As in the economic assessment, battery production and battery operation (electricity loss due to inefficiencies) are considered, while the end-of-life handling of the batteries is neglected, mainly due to insufficient data availability about recycling processes.

The functional reference of energy storage is each kWh withdrawn from the grid or RES unit depending on the scenario. The calculation is comparable to LCC calculation wherein costs €/kWh are substituted by a specific environmental impact EI_{nkWh}. Total environmental impacts over the entire life time of a specific system component EI_{kWh} (e.g., battery, PV or wind turbine) are summed up and divided by the sum of the provided energy P_n by a particular component (e.g. generated through RES, converted by the battery or directly provided by the grid) as shown in Equation 18

$$EI_{kWh} = \frac{\sum_{n=1}^{n} EI_n}{\sum_{h=1}^{h=8640} P_n} \qquad \textit{Equation 16}$$

It is difficult to choose different environmental impact categories as an MCDA criterion. There exists a high number of different impact categories as noise, non-methane volatile organic compounds or land use and others which can be hardly prioritized by a broad stakeholder group just due to missing knowledge (it is challenging to, e.g. rank eutrophication against land use). Furthermore, the choice of a limited number of criteria might lead to non-representative results (e.g., on technology option might only have greenhouse gas emissions but large ones regarding water toxicity). A question related to this set of criteria was thus how to provide aggregated criteria that can be simply understood by participants and allow a comprehensive assessment of potential environmental impacts.

There is a set of well-known methodologies available for LCA as Eco-Indicator 99 for endpoint indicators (endpoints and single score) and CML 2002 for midpoint indicators (greenhouse gases, ozone depletion, etc.) [267]. Recipe is a follow-up of these two methods. It combines and harmonizes midpoint and endpoint approaches, and all impact categories have been redeveloped. Recipe allows users to choose their level of result through eighteen midpoints which are relatively robust, but not easy to interpret. Thus three simple to understand, but more uncertain endpoints where introduced in the method [268]. It is recommended to rather use mid-point impacts for detailed analysis as end-point results are difficult to interpret and considered more uncertain in relation to the first [269]. An overview of recipe principles is given in Figure 7-16.

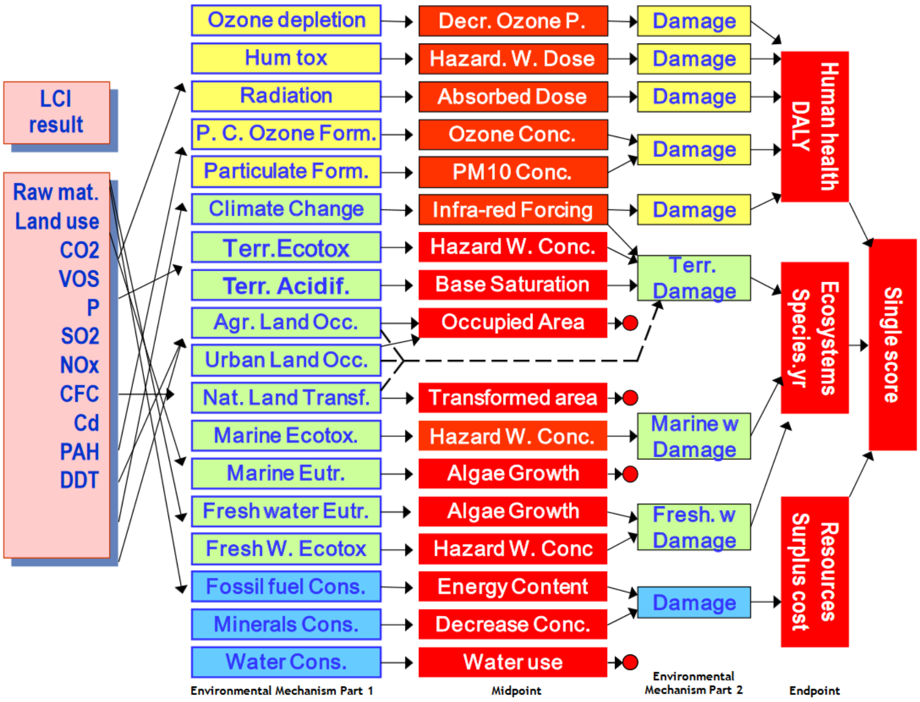


Figure 7-16: LCI results (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008 [268].

The recipe endpoint method is complex and is thus only explained roughly in this context. Detailed information can be found in [269], [268]. All endpoints used as criteria for this work can be briefly summarized as follows [268]:

- **Damage to Human health (DHH):** using the concept of „disability-adjusted life years“ – DALY (yr). The DALY of a disease is based on human health statistics on life years lost and disabled including various cancer types, vector-borne diseases, and non-communicable diseases.
- **Damage to ecosystems (DE):** based on the loss of terrestrial, freshwater and marine species during a specific time in a specific area (yr).
- **Damage to resource availability (DRA):** describes the risk of humanity running out of resources for future generations. It is based on the geological distribution of resources and the marginal increase of extraction cost ($)

The method offers the possibility to include different perspectives on the considered time frame which are as follows: Hierarchist perspective (100 years) is considered as the default option which is frequently used and referred to in [160]; Egalitarian (500 years) for a long term view (e.g., to consider the atmospheric life time of certain substances); and finally Individualist perspective for short-term perspectives (20 years) [267]. The standard Hierarchist perspective is taken into account in this work.

Most of the interviewees (one exception) thought that these three criteria are easy to understand and that it makes sense to use them rather than to weight a selection of midpoint criteria.

7.7.1 Life cycle inventory for energy storage technologies

The impacts associated with battery, PHS, and CAES production are calculated based on present LCA studies. For this purpose, the inventory data provided by existing studies are recompiled and unified by using identical average values for common battery components in the case of LCA [91]. This improves significantly the comparability of the results from different individual studies [270]. Although some of the LCI disclosed by these works represent Li-Ion battery packs for electric vehicles, it is assumed that a stationary energy storage system would use battery modules of a similar configuration in a modular array.

The inventory for the PbA is based on the recent work of Spanos et al. [271], an LCA study about battery for stationary demand-charge reduction. While a NaNiCl battery is contained in ecoinvent, the corresponding inventory is very simple, and therefore an alternative LCI is used, based on the works by Longo et al. [272], Galloway et al. [273] and Sudworth et al. [274]. No recent LCA study on VRF batteries is available, why a rather old work is used with comparably simple LCI for this type of battery [265] and additional information regarding the battery layout from a recent cost study published by [275] as well as the production of Vanadium Pentoxide based on [276]. As in the case of LCC, a linear correlation of membrane (Nafion-membrane) area and amount of electrolyte is assumed for impact calculation of the VRF battery, based on the energy to power ratio. The limited availability of reliable data and thus the higher uncertainty in the inventories of the non-lithium batteries (VRLA, VRF, and NaNiCl) has to be taken into account when comparing results. The LCI for CAES is taken from [94] and rescaled in a linear way for the case of ETS. Leaching far salt caverns was excluded as it is assumed that CAES represents a second use case. The original ecoinvent data [277] set for PHS construction was taken as a starting point and is as in the case of CAES linearly rescaled linearly for comparison reasons.

The three recipe endpoints obtained with these inventory data for the different battery types, CAES and PHS are given in Table 7-16. Robustness of the used datasets is also rated qualitatively by the use of a traffic light principle where red indicates poor, orange medium and green good. High impact discrepancies can be observed per kWh of energy storage capacity due to different energy densities of each technology. The environmental impact of battery production is associated with the amount (the mass) of battery that has to be produced. For a low energy density battery, a higher amount of material is required for providing the same capacity, increasing the impacts correspondingly due to a high conversion factor (CF). A detailed breakdown of the environmental impacts of battery production to single battery components and thus the primary drivers for impacts can be found in a previous publication [270]. VRLA and VRFB show very low impacts per kg of battery produced, mainly due to their simplicity (in the case of VRF, the overwhelming mass share of the battery consists of tanks filled with liquid electrolyte), while their low gravimetric energy density reduces these advantages on a per kWh basis, especially for the VRFB. It has to be mentioned that the LCI of VRFB is based on an energy to power ratio of 9:1, while with a lower ratio, the share of the electrolyte of the total battery mass would decrease. Consequently different environmental impacts would result from a different E/P ratio.

In most of the underlying studies, no probability distributions or uncertainty information are given together with the provided inventory data or the LCA results. Thus, for the calculations of the three recipe end-points of the considered systems, a deterministic approach is used with static impact factors for each battery type except LFP and NCM. For these, at least two works are available and thus a value range that can be considered.

Table 7-16: LCI sources and resulting recipe impact factors per produced kWh of storage, where DHH=Damage to Human health, DE=damage to eco-systems; DRA=Damage to resource availability

Techn.	Wh/kg	CF[1].	DHH	DE	DRA	Source	Unc.[2]	Comment
LFP[3]	96.1	10.6	9.48	3.21	6.48	[278], [279], [270]	Low	Good documentation
LTO	52.3	19.1	13.67	5.64	11.06	[270], [280]	Low	Good documentation
NCM	134.7	7.18	10.46	9.45	9.45	[281], [278], [270]	Low	Good documentation
NCA	133	7.51	4.652	1.82	5.58	[270], [280]	Low	Good documentation
VRLA	45.1	22.15	5.23	1.15	9.71	[271]	High	LCI very superficial
NaNiCl	112.5	8.88	7.74	1.18	7.131	[272], [273], [274]	Med.	No comparison av.
VRFB	17.5[2]	57.12	29.44	4.54	15.11	[265], [275]	High	Very old source
NaS	116	8.62	5.30	2.08	6.39	[282], [283], [272]	High	LCI very superficial
PHS	-		5.04	4.76	1.02	[277]	Med.	No comparison av.
CAES	-		8.94	6.12	4.56	[94]	Med.	No comparison av.

[1]Conv=Conversion factor; [2]Unc=Uncertainty; related to E/P ration of 1/9; [3]Average from [278], [279], [270]

For determining impacts associated with electricity generation, the ecoinvent 3.2. dataset "electricity, EU w/o CH" is used for the reference year (2012) [284]. Naturally, this applies only to the two application fields where grid electricity is used; for the application field 'Wind Energy support' a 3 MW onshore wind turbine is used. Inverters are taken from Ecoinvent 3.2 but had to be rescaled as the database only provides 3 kW or 500 kW sized ones. Also for the HMGS case ecoinvent 3.2 only provides data for wind turbines with a capacity of 750 kW and PV panels with a minimum size of 3 kWp. These components are thus also re-scaled linearly to the assumed size within the considered application cases. Admittedly, this represents a conservative and simplifying assumption but can be considered necessary due to the lack of more precise data in this regard. More details about the LCA can be found in recent publications related to this work [89], [91] and [285].

7.7.2 LCA Results

The LCA results for the different application for all impact categories, cases and the contribution of the different life cycle stages are given in Figure 7-17. Again, box plots show as in the case for LCC the 5 % and 95 % percentiles, 25 % quartiles; median and 75 % quartiles and provide an idea of the uncertainties associated with the given calculations. The following interpretation of results has been recently published in [286] in the line of this research and is thus only discussed briefly. A detailed overview of numeric MCS-LCA results is given in Annex D.

The availability of LCI data for VRFB is limited (little data or very simplified modeling) and the corresponding results should be interpreted with care. The results obtained for the LCA differ quite remarkably from those of the LCC, with a clear distinction between two system approaches: (i) Systems that use renewable electricity (HMGS and RS) and (ii) systems based on grid electricity (ETS and PR). This indicates the importance of the use phase (energy consumption during operation due to internal losses) for the final LCA results. HMGS and RS show very similar profiles, although the contribution of the different life time phases varies slightly. Especially the use phase has a lower contribution as wind electricity shows a small environmental burden than PV based one, why the contribution of internal energy consumption due to inefficiencies has a lower weight. ETS and PR have comparable impacts as the charged electricity is assumed to be based on the European electricity mix which has a considerable higher environmental burden in relation to the renewable energy for HMGS and RS.

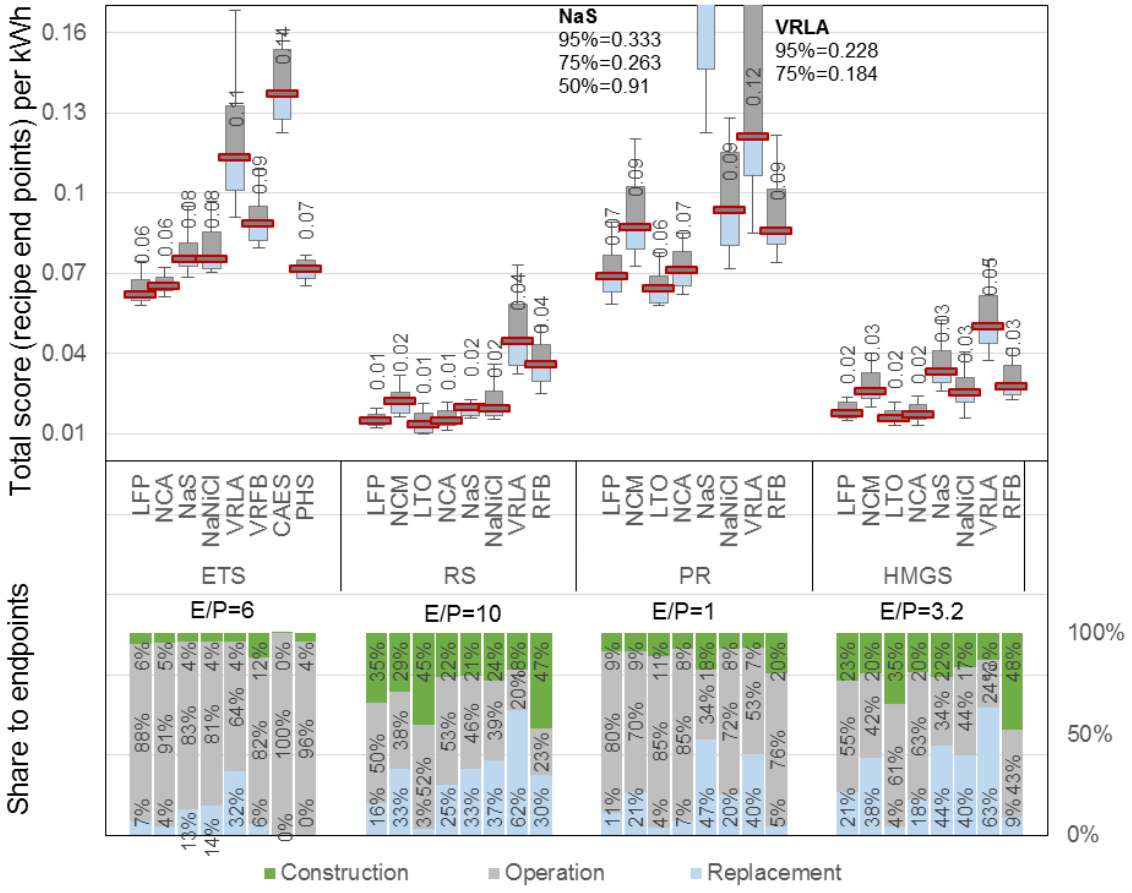


Figure 7-17: LCA results for all technologies and application cases and main shares to total impact

Comparing the different LIB types, NCM shows a high endscore for all application cases where it is considered. Correspondingly, the high cycle life of the LTO and LFP leads to very good results for these two battery types in all applications. Like for LCC, where the initial investment costs of LTO are significantly above those of other LIB, the recipe end-score for LTO battery production is also higher. Nevertheless, the difference over the entire life cycle is lower, and the higher cycle life time and a low minimum SOC can compensate for this in all applications. VRLA has, despite its very low impacts from cell production, a very high environmental impact over its life time. This is mainly due to relatively low cycle life time and low-efficiency grades, requiring heavy oversizing in all cases. Also, VRFB show comparably low-efficiency grades, leading to higher energy consumption and thus a higher environmental burden over the entire life time, especially for the grid-electricity based application (ETS). An interesting difference regarding VRFB in relation to other battery types (and a result contrary to that for LCC) is that the impact increases for applications with a very high E/P ratio (e.g., RS). A high E/P ration requires proportionally high amounts of vanadium pentoxide (V_2O_5) electrolyte, associated with environmental burdens for its production. It has to be mentioned that the results of VRFB are associated with a high uncertainty as in the case of LCC. In this work, V_2O_5 is assumed to be obtained from slag from an iron production process by roasting with NaCl or $NaCO_3$, leaching with ammonia, alumina-thermic reduction and electron-beam melting [276]. This leads to a high overall impact for VRFB in cases with a high E/P ratio, while other ways like obtaining it from petroleum or refinery slags or a by-product of uranium mining [287], might give different results. Since these different modeling approaches cannot be represented by uncertainty distributions, they are also not reflected in the uncertainty distributions of the recipe final scores.

Impacts for NaS are very high for the case of PR due to the fixed E/P ratio and the resulting considerable oversizing of capacity (factor 6). This also comes true for the HMGS application case where the battery scores next to last to VRLA. Results with higher E/P ratios show better results which are comparable with those from NaNiCl as in the case for RS.

PHS is characterized by low impacts despite its comparatively low-efficiency grades which can be explained by the long-life time of this technology of up to 90 years. CAES has the highest impacts in this application field due to low-efficiency grades and the combustion of natural gas. It has to be mentioned that future works should consider adiabatic CAES where no combustion is required due to the use of storage units to store heat resulting from compression which is then used for heating in case of air expansion.

The share of the different impact categories in relation to total scores are given in Figure 7-18. It can be seen that overall impacts come from DRA and DHH dominate in all cases. A brief overview of the main categories and their overall share on total scores is given in the following as it is not possible to present a detailed picture of all impact categories for each technology and application case.

DRA: Is characterized by two categories namely metal and fossil depletion. The first category describes the additional net present costs that society has to pay as a result of extraction and has a significant share in almost all battery storage technologies. Fossil fuel depletion refers to resources including hydrocarbons (liquid petrol, methane, etc.) and is strongly dependent on the provided electricity mix (e.g., ENTSO-EU mix vs. electricity from wind turbines corresponds to a factor of 24 or a factor of 5.3 for PV. The case of metal depletion though is contrary, and RES show a higher depletion in this category. VRLA shows the highest DRA among all battery storage technologies as the battery is considerably oversized to assure a sufficient high cycle life time to avoid cell exchange. NaS and NaNiCl have comparable results, where only HMGS and PR show differences due to the oversizing of the first related to limitations of E/P ratio. Total scores of all battery technologies are dominated by cell production. Fossil fuel is one of the main contribuents in the case of CAES.

DHH: the final score of almost all technologies is strongly influenced by climate change (e.g. radiative forcing in $CO_{2equivalents}$, temperature effects damage to human health (malnutrition, cardiovascular disease etc.)), followed by human toxicity (the environmental persistence and accumulation in human food chain, and toxicity of a chemical) and particulate matter formation (includes a magnitude of organic and inorganic substances (e.g. SO_2 NO_x, NMWOC etc.)). One exception is VRLA and NMC where the human toxicity dominates. This is mainly due to the use of lead (88% share) for VRLA and related to cell production in the case of NMC. In general, cell production contributes the most significant share to climate change and particulate matter formation for all batteries. Again, total scores in this category are highly dependent on the considered electricity mix. Especially CAES shows here high impacts due to the additional combustion of natural gas.

DE: The highest impacts are also as in the case of DHH related to climate change (related to ecosystems and the loss of species (mainly plants and butterflies)), followed by agricultural, urban, natural and agricultural land occupation (occupation of transformed area and related loss of species over a given period time required for restoration and the impact on the number of species on that area [268])). Especially the latter is relatively high for PHS due to the need for a lower and upper water basin. Climate change contributes the main share for all technologies within this endpoint. Technologies with low-efficiency grades tend to have higher impacts in this category due to increased energy consumption. As in the other cases, this factor is strongly dependent on the electricity mix considered.

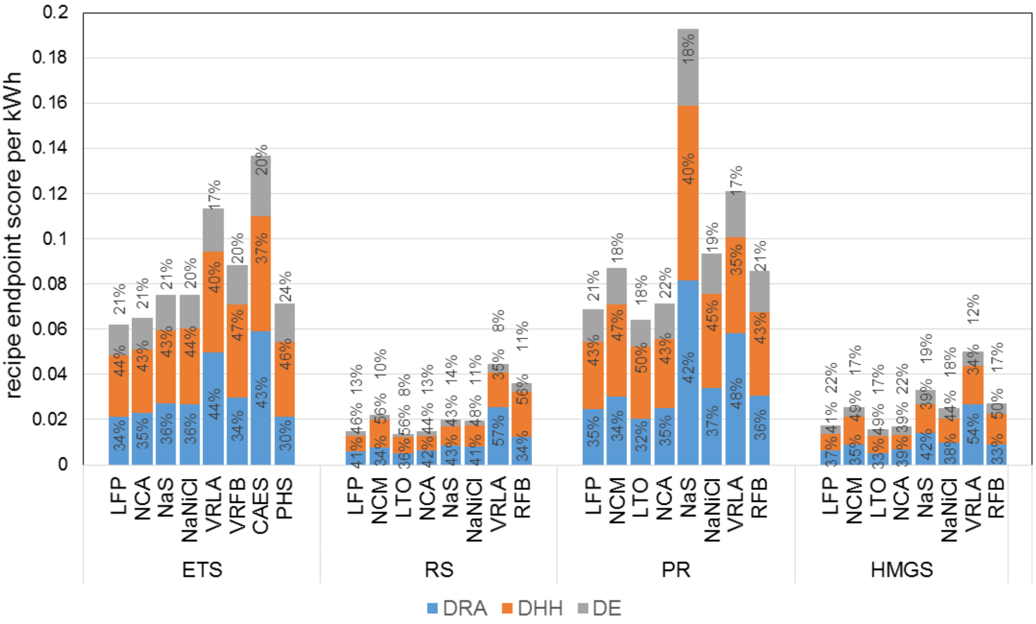


Figure 7-18: Share of endpoints to total score for all technologies and application cases (median values)

7.7.3 LCA - sensitivity analysis for HMGS

The sensitivity of recipe endpoint results in dependence of major battery storage parameters within a range of -20% to 20% around median values is given in Figure 7-19. Again, LFP is taken as a reference, and positive changes of parameters are indicated in dark grey and negative ones in light grey. Variation of recipe scores is related to the median value of 0.02. It can be seen that decreasing efficiency grades increases environmental impacts significantly. Reducing impacts during cell production leads to significant reductions in total impacts. Comparable impacts can be observed for cycle life time and energy density where increasing parameters lead to environmental benefits.

The detailed sensitivity analysis (as previously for LFP in HMGS) shows that results are, as for the LCC, highly dependent on operation hours and thus the amount of energy stored per year (Figure 7-20 A). Relevance of efficiency grades is highly dependent on the environmental burden of the charged electricity in the case of HMGS (determined by the share of PV or micro wind turbine), and its influence only increases for minimal use-intensive applications (low amounts of energy stored per year). This is due to the increasing weight of battery production since for a low-efficiency battery the losses have to be compensated for by oversizing correspondingly (the basis of comparison is the net electricity provided by the battery).

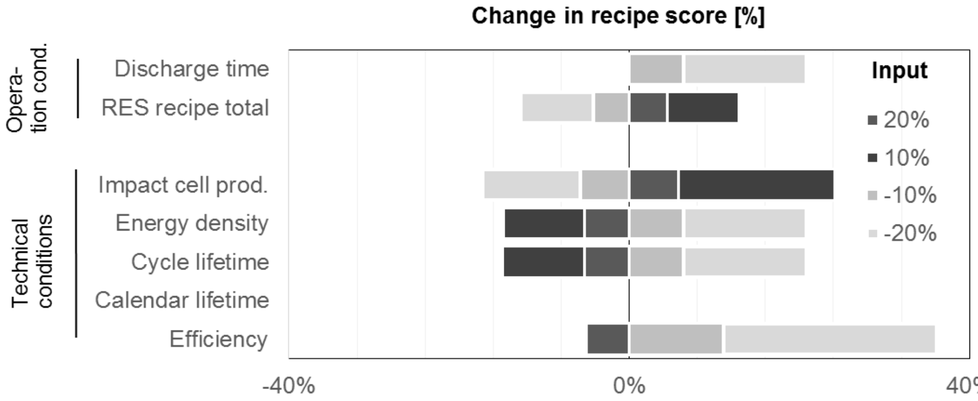


Figure 7-19: Sensitivity of recipe endpoint results to different parameters of battery operation and properties (inspired by [5])

The recipe endpoints allocated to the charged electricity is of paramount importance for the total environmental impacts of the system and has a comparable impact to the impacts caused by the battery production process (Figure 7-20 B). A comprehensive sensitivity analysis of different operating conditions in ETS, RS, and PR and resulting environmental impacts is also provided in [190] for greenhouse gases.

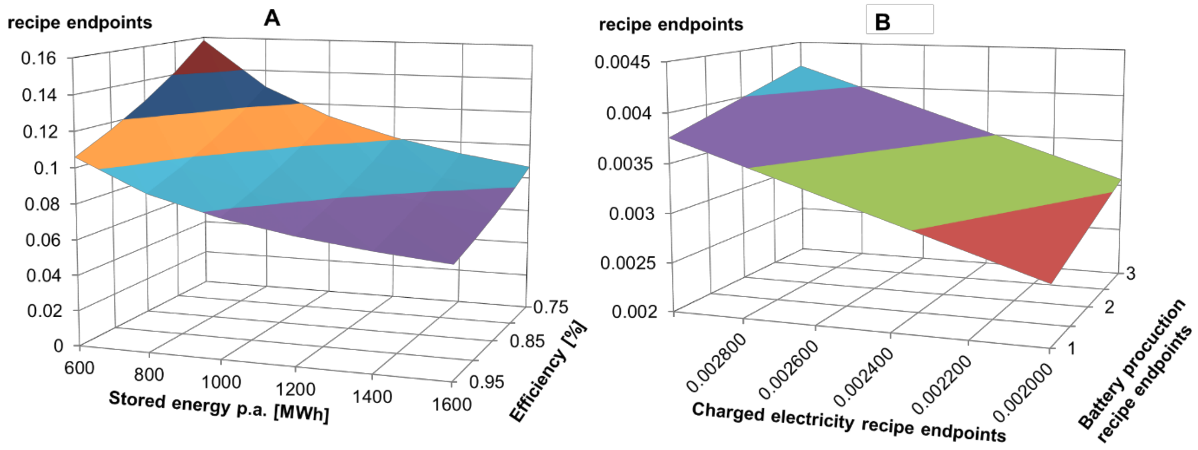


Figure 7-20: Sensitivity analysis for RS with LFP A) battery production vs. charged electricity B) Variation of efficiency and total stored energy per year

7.8 Discussion of technology evaluation

The chapter provided an overview of effects and impacts of different energy storage technologies in selected applications regarding the identified criteria and use cases within the MCDA process. Figure 7-21 provides an overview of all considered criteria, the way of quantification as well as comments related to the issues which occurred during technology evaluation presented before. Based on this experience the quantification methods used are rated regarding their perceived robustness and state of knowledge and indicate the potential for future research. This is simply done qualitatively by a traffic light system where red indicates low knowledge, orange a moderate and green a good robustness as well as the availability of data.

Social factors represent the most uncertain criterion due to missing literature and knowledge related to energy storage in this context. Especially local acceptance is a relatively new area when it comes to end-user near decentralized stationary battery storage. It is difficult to find standard definitions in literature as there are highly different notions when it comes to the factor of, e.g. “public acceptance.” Some examples for factors which increase the willingness to adopt a technology (or to accept it) from literature which can be named in this regard are the works of [99] and [100] which have been introduced in chapter 2.8. In general, expectations of the public about low cost and environmental impacts and properties of different technologies have a high impact on their technology acceptance [207]. Every criterion used for this technology evaluation can thus be seen as a relevant aspect and is highly interdependent from others which in sum may contribute to the overall “acceptance“ or willingness to adopt a technology.

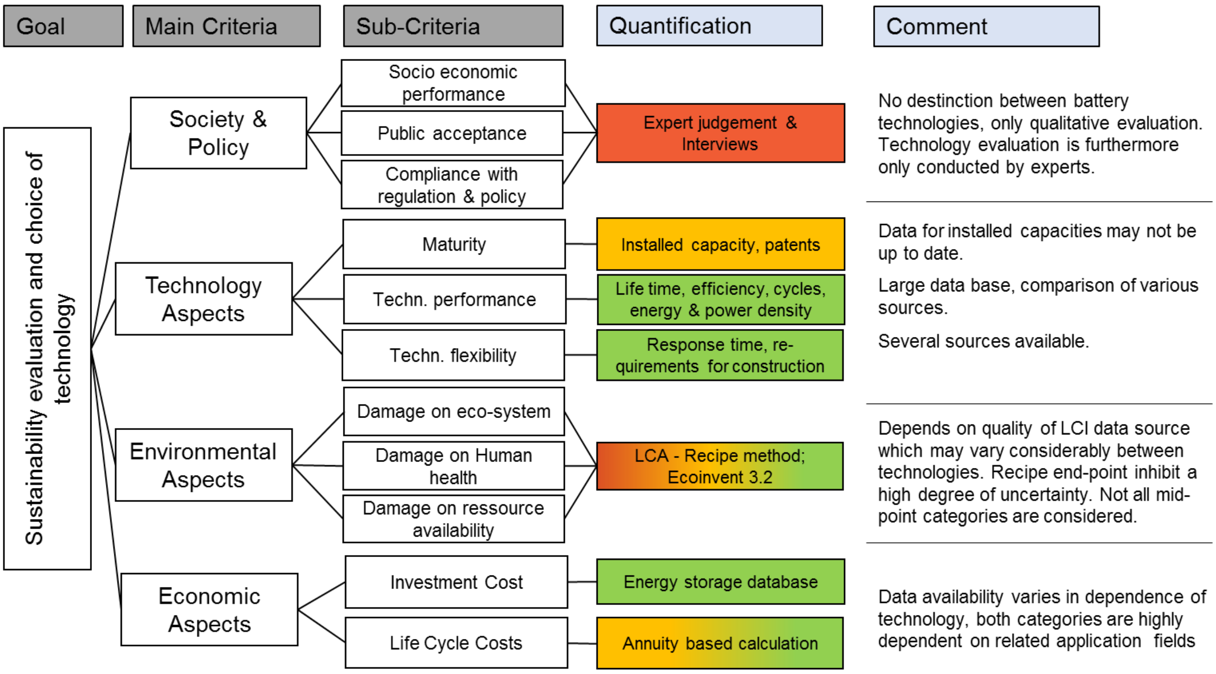


Figure 7-21: Summary of all indicators and quantification methods used for technology evaluation in frame of the MCDA and the perceived uncertainty of these (own estimation)

The robustness and state of knowledge related to LCA results are highly dependent on the availability of data which is not the case for some technologies (e.g., RFB, NaS or CAES), where more research efforts are required. A more in-depth analysis should thus be conducted based on mid-point indicators to obtain a more comprehensive picture of the impacts related to the technologies assessed. Economic aspects seem to be relatively robust as there is already a certain degree of literature available. It remains however difficult to find representative application fields for different electrochemical energy storage technologies. This comes mainly true when dynamic cycle life time is considered.

The intermediate results and the sensitivity analyses point out the importance of cycle life and internal efficiency of battery systems for their environmental impacts and costs (LCC). This corresponds to the findings by Hiremath et al. [288] and Battke et al. [210], who assessed the environmental impacts and LCC of different battery types in stationary applications. In line with these works, initial investment costs and battery replacement are found to be the primary drivers of costs (LCC). Therefore, the LCC results depend to a significant share on the battery cell costs, while for the LCA, the battery efficiency (charge-discharge losses during operation) is of paramount importance, especially when buffering electricity with a substantial environmental backpack.

8 Results

The literature review has shown that most studies concerned with decision making regarding energy storage do not consider socio-technical dynamics and instead focus on small homogenous expert groups. It is postulated that CTA can help to break through typical enactment cycles by shifting the locus of assessment towards a broader perspective to provide a base for social learning to create “better” or sustainable technology in a “better” society.

Stakeholder priorities regarding technology properties quantified in the chapter before are obtained by pairwise comparisons within AHP which will be presented in the following sections. One of the aims of this work is to identify if there is there are common expectations about these characteristics that energy storage technologies should possess. A high “sharedeness” of expectations ensures that stakeholders act accordingly to these expectations. AHP judgments serve as a base to calculate the consensus which represents the level to which a group is satisfied by a decision. This requires that judgments are homogenous and that the priorities expressed by individual group members are compatible with the group priorities [181]. The degree of this consensus can serve as a starting point for further stakeholder interaction to achieve alignment. A further target of this work stated in chapter 4 is to identify which technologies perform the “best” in the face of identified criteria and application cases. AHP priorities and technology evaluation results are used as an input for TOPSIS which serves as aggregation method to calculate overall technology performance. A special focus is put on the case of HMGS due to the high relevance attributed by actors to decentralized use cases (see chapter 5.6). An open question is how to use given results to inform actors to achieve something like “better technology” and to enable something like “social learning.”

The following chapter provides the results of the MCDA inquiry, presenting overall and specific group preferences and their degree of consensus. Resulting scores through the combination of technology evaluation and AHP through TOPSIS are given in the following section. Then, a sensitivity analysis of varying weights and model assumptions for HMGS to provide insights into changes of rankings is given. Finally, a summary of results is provided and discussed.

8.1 General priorities and consensus

The prioritizations, including insights to mean, min, max, medians, standard deviations and consensus for all stakeholders and criteria are indicated in Table 8-1. Median values for priorities are taken for further calculations related to technology evaluation. All categories include the consensus of prioritizations regarding the sub-criteria as, e.g. damage to human health, to ecosystems and resource availability as in the case of environmental impacts. A high consensus up to 100 % indicates a high degree of consensus or “sharedness” of the perceived characteristics technology should have, >75 % can be considered as high. Around 50 % represents modest consensus and <30 % can be considered as very low.

Results for median priorities related to the main criteria indicate a high preference for economic aspects (0. 241) and environmental impacts (0. 236). It is interesting that stakeholder almost attribute the same importance to these two criteria as a strong preference towards economic aspects was perceived. It must be mentioned that average values indicated the contrary standard deviation shows that a rather high variance of perceptions of different stakeholders is given. This may be explainable by the comments given by interview participants which indicated, that environmental impacts can also represent a crucial impact on overall project costs in case of unforeseen severe environmental impacts. Technology performance aspects are ranked third related to their perceived importance (0.197). The least importance is attributed to social aspects (0.131) which seem to play a little role when it comes to the relevance of storage technology properties. Standard deviation is the highest for first two main criteria and is significantly lower for last two. This also comes true for maximum priorities (0.59 vs. 0.7). The consensus is with 42 % is rather low and indicates that there is no real common perception regarding these four criteria among all participants. Consistency (GCI) of overall results is very high (0.115).

The category of environmental impacts shows a clear dominance of potential impacts related to the recipe category of human health (0.472). This criterion is followed by damage to eco-systems (0.263) and finally resource use which was weighted the lowest (0.146). Here, standard deviation, minimum and maximum preferences are comparable for all criteria. Total consensus though is low with 37.9%, indicating that there is the need for a more in-depth discussion with participants whereas consistency of AHP comparisons is at an average level.

Social acceptance, as well as socio-economic value, are perceived as equally important (0.33) within the field of social aspects, which are ranked the lowest in relation to the other categories. Regulatory frames received the lowest priority (0.2). The latter is not necessarily seen as a prerequisite for technology success through the eyes of some participants (compare with chapter 6), but on the other hand missing regulation is often named as an obstacle when it comes to technology introduction. In general, standard deviation was very high for all criteria, and consensus shows a low degree of shared expectations in this category.

The criterion of “Technology aspects” is ranked third among the other main categories. Again, consensus is very low (32%), which also comes true for the consistency of given priorities (0.310). This indicates that is was difficult for stakeholders to attribute clear priorities to each of these criteria within the pairwise comparisons. Maturity and technology flexibility are seen as highly relevant (0.33 for both). Technology performance has received a slightly lower priority (0.283). Especially maturity shows high deviations regarding the given priorities (0.214).

Results for economic criteria show clearly a higher perceived importance for cost in relation to investment costs (0.200 vs. 0.800). There is no consensus among the stakeholders about the relevance of these two criteria which is a surprising result as the contrary was expected based on the interviews where LCC where often named as a relevant parameter for investment decisions. An explanation for this may be that these two criteria can be seen an arbitrary and thus as challenging to rate for stakeholders, or that indeed some stakeholders have a rather short-term perspective on investment decisions (expressed by a high rating towards investment costs). The GCI for economic factors is 0 as only two criteria are compared to each other.

Table 8-1: Overview of overall weights obtained through AHP for all stakeholders n=69

Category	Criteria	Median	Mean	Min	Max	STDEV.	Average GCI	Consensus
Main Criteria	**a)** Environment	**0.236**	**0.276**	0.038	0.700	0.142	0.115	42%
	b) Social Aspects	**0.131**	**0.170**	0.038	0.509	0.095		
	c) Technology	**0.197**	**0.206**	0.038	0.590	0.108		
	d) Economics	**0.241**	**0.271**	0.038	0.700	0.142		
a) Envrion-mental impacts	Eco-system	**0.263**	**0.290**	0.037	0.773	0.141	0.132	37.9%
	Human health	**0.472**	**0.485**	0.037	0.773	0.169		
	Ressource use	**0.146**	**0.193**	0.037	0.662	0.169		
b) Social performance	Social acceptance	**0.333**	**0.364**	0.052	0.750	0.192	0.145	34.3%
	Socio econ. value	**0.333**	**0.371**	0.052	0.750	0.194		
	Regulatory frame	**0.200**	**0.239**	0.052	0.745	0.165		
c) Technology performance	Maturity	**0.333**	**0.341**	0.051	0.750	0.214	0.310	32.9%
	Flexibility	**0.333**	**0.346**	0.051	0.678	0.163		
	Performance	**0.283**	**0.277**	0.051	0.662	0.153		
d) Enconomic Performance	Investcost	**0.200**	**0.324**	0.100	0.900	0.242	0.000	0.0%
	LCC	**0.800**	**0.676**	0.100	0.900	0.242		

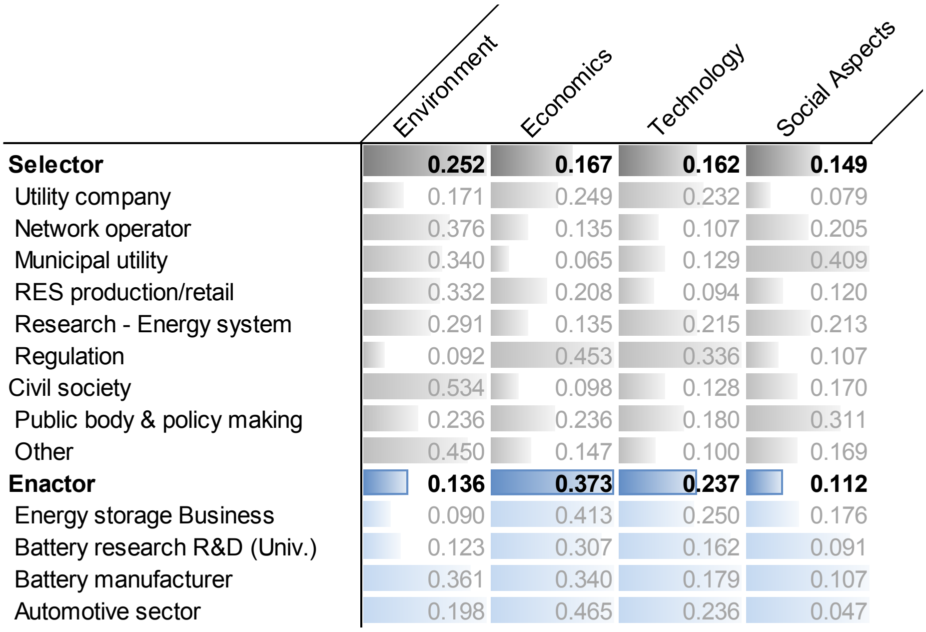
8.2 Group preferences and consistency

Numeric values of preferences of enactors and selectors are given in Table 8-2 to provide detailed insights into resulting priorities as vectors had to be rescaled for graphical reasons regarding the four main criteria in Figure 8-1. Results from AHP show that selectors have profoundly different expectations on technology properties in relation to enactors which will be discussed separately in the following. The matrix in Figure 8-1 is calculated in orientation towards the Boston Consulting Group (BCG) matrix and allows “to map” stakeholder´s preferences and consensus regarding the four main criteria in a simple way. The location of the bubble is based on the four vectors attributed to each criterion by every stakeholder group. A group does not have a strong preference for any criterion if, e.g. a bubble is situated nearby the middle of the 4-field matrix. Labeling of bubbles includes the number of valid prioritizations (1 to n) then the type of stakeholder group and finally the resulting consensus factor within the entire group in %, which is also expressed in a bubbles size (the bigger it is, the higher is the consensus).

The selector sub-group preferences (see Table 8-2 and Figure 8-1) are highly diverse. In total, there is a stronger preference towards environmental aspects and relative comparable priorities for technology, economics, and social aspects. As stated in the theory chapter, comparative indicators for technology selection as environmental and social impacts are more relevant for this actor group [141] [20]. Total consistency for selectors is 40% which can be considered as low. It is difficult to provide a representative picture of all stakeholder sub-groups due to the low response rate or non-sufficient consistency of prioritization of some single groups. It is evident that 1 participant will achieve a consensus of 100 % as in the case of public body and policymaking. The two candidates from “Regulation” (lower right quadrant) and “Municipal utility” show a very high and moderate consensus with 97 % and 74 %. The latter shows a strong tendency towards social aspects which also comes true for the one stakeholder from policymaking. The group of utility companies including 11 valid datasets has a low consensus of 35 %

with a stronger tendency towards the importance of technology and economic aspects of energy storage technologies.

Table 8-2: Priorities from enactors and selectors as well as related subgroups



	Environment	Economics	Technology	Social Aspects
Selector	**0.252**	**0.167**	**0.162**	**0.149**
Utility company	0.171	0.249	0.232	0.079
Network operator	0.376	0.135	0.107	0.205
Municipal utility	0.340	0.065	0.129	0.409
RES production/retail	0.332	0.208	0.094	0.120
Research - Energy system	0.291	0.135	0.215	0.213
Regulation	0.092	0.453	0.336	0.107
Civil society	0.534	0.098	0.128	0.170
Public body & policy making	0.236	0.236	0.180	0.311
Other	0.450	0.147	0.100	0.169
Enactor	**0.136**	**0.373**	**0.237**	**0.112**
Energy storage Business	0.090	0.413	0.250	0.176
Battery research R&D (Univ.)	0.123	0.307	0.162	0.091
Battery manufacturer	0.361	0.340	0.179	0.107
Automotive sector	0.198	0.465	0.236	0.047

This might be explained by the heterogeneity of this subgroup which also comes true for the group “Others” with a consensus factor of 35 %. Stakeholders from “Research Energy System” had a strong orientation towards environmental aspects with a balance of social and technical aspects with a low to moderate consensus of 62% for 8 participants. Civil society had the strongest orientation towards environmental aspects with a comparably high consensus of 73% with two participants.

Enactors show a stronger tendency towards economic and technical aspects and subgroups can be considered as more homogenous regarding their priorities. Results prove that the enactment frame leads them to concentric thinking about desired technology properties. This impression is reinforced through a low consensus factor of 53 % for the entire group. The energy storage business participants achieved a high (low to moderate) consensus of 72%, while battery storage manufacturers and academic research achieved a low degree of 53% and 41%. The average preferences of enactors have a clear techno-economic orientation. One exception are battery manufacturers who seem to have a very balanced preference towards environment and economics.

The total consensus of 45 % for all actors is low and indicates a more or less different notions about the importance of economic and environmental aspects of storage technologies. Technology aspects are in total considered as more important in relation to social aspects as described in the chapter before.

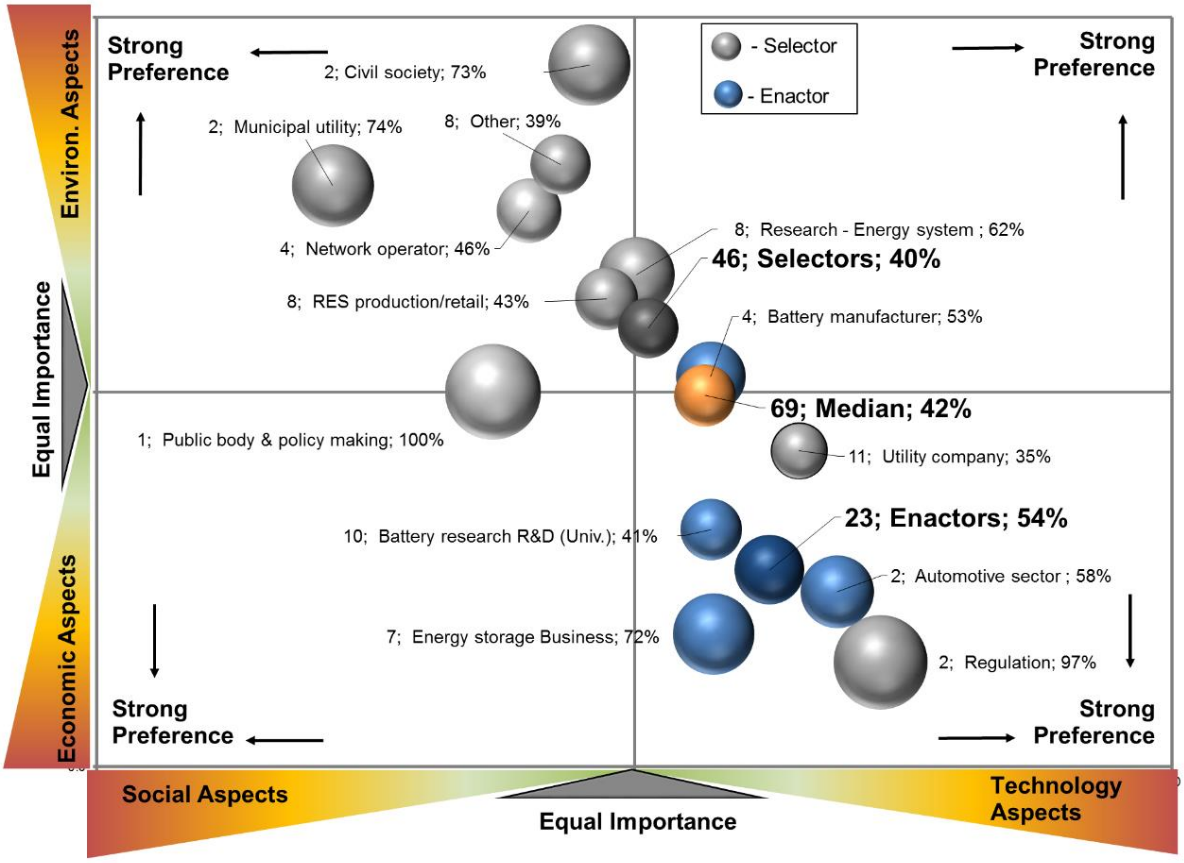


Figure 8-1: Consensus of different stakeholder groups and their median orientation towards the four given main criteria for technology design, note that only valid entries have been included with N=69

Details to preferences and consensus of enactors and selectors as well as related subgroups for sub-criteria are given in Table 8-3. Most enactors and selectors see LCC as a critical criterion for technology choice in relation to investment cost within economic aspects. The consensus is very low for both groups; enactors and selectors. Some exceptions are given for network operators and automotive sector. Comparison of environmental impact factors shows a substantial importance to the criterion of “human health” among the other two factors within this sub-group. One apparent exception is civil society, where two participants from NGOs took part and perceive “low damage to ecosystems” as most relevant as a technology characteristic. The consensus is high for most of the groups, despite the automotive sector. Criteria for social aspects are almost equally weighted for enactors and selectors with a low consensus, whereas some of the sub-groups as battery manufacturers achieved high values. Criteria related to technology aspects are weighted more differently between enactors and selectors. The latter seem to lay more effort on technology performance whereas enactors perceive the technology maturity as very important, which comes mainly true for battery manufacturers. It is interesting that in general priorities and consensus of subgroups vary remarkably. This variation shows that interests are profoundly different among the subgroups related to enactors and selectors.

Table 8-3: Prioritizations of sub-criteria and related consensus factor for enactors and selectors including all 13 stakeholder (SH) subgroups.

		Env. aspects				Social aspects				Techn. Aspects				Econ. Aspects		
Stakeholder	No of SH	Ecosystem	Ressources	Human Health	**Consensus**	Social accept.	Socio-econ.	Reg. frame	**Consensus**	Techn. Maturity	Techn. Perf	Techn. Flex.	**Consensus**	Investm. Cost	LCC	**Consensus**
Selectors	40	**0.28**	**0.14**	**0.46**	**65%**	**0.33**	**0.33**	**0.20**	**41%**	**0.31**	**0.33**	**0.29**	**40%**	**0.18**	**0.82**	**2%**
Utility company	10	0.26	0.18	0.54	0.56	0.17	0.49	0.19	0.10	0.38	0.25	0.14	0.11	0.13	0.88	0.00
Network operator	4	0.25	0.10	0.58	0.75	0.54	0.34	0.11	0.58	0.14	0.35	0.44	1.00	0.14	0.86	0.95
Municipal utility	2	0.53	0.11	0.32	0.67	0.64	0.27	0.08	1.00	0.07	0.47	0.47	1.00	0.18	0.83	0.64
RES production/retail	8	0.27	0.10	0.53	0.47	0.60	0.26	0.13	0.31	0.31	0.29	0.28	0.32	0.17	0.83	0.00
Research - Energy system	8	0.33	0.30	0.33	0.33	0.33	0.33	0.33	0.35	0.33	0.33	0.33	0.66	0.18	0.82	0.20
Regulation	3	0.09	0.18	0.68	0.80	0.31	0.21	0.47	0.00	0.57	0.21	0.19	0.83	0.48	0.53	0.00
Civil society	2	0.55	0.08	0.33	0.67	0.36	0.42	0.18	0.00	0.20	0.35	0.35	0.00	0.18	0.83	0.64
Publ. body & pol. making	1	0.40	0.20	0.40	1.00	0.33	0.33	0.33	1.00	0.33	0.33	0.33	1.00	0.50	0.50	1.00
Other	8	0.38	0.12	0.45	0.69	0.33	0.33	0.19	0.46	0.15	0.48	0.31	0.62	0.20	0.80	0.00
Enactors	23	**0.18**	**0.16**	**0.57**	**14%**	**0.33**	**0.33**	**0.24**	**12%**	**0.33**	**0.29**	**0.22**	**25%**	**0.25**	**0.75**	**0%**
Battery manufacturer	4	0.17	0.18	0.56	0.28	0.23	0.58	0.16	0.77	0.62	0.22	0.10	0.35	0.25	0.75	0.00
Battery R&D (Univ.)	10	0.17	0.18	0.56	0.35	0.45	0.33	0.13	0.28	0.33	0.33	0.21	0.14	0.25	0.75	0.19
Energy storage Business	7	0.17	0.17	0.60	0.90	0.33	0.29	0.33	0.43	0.27	0.33	0.32	0.49	0.50	0.50	0.06
Automotive sector	2	0.11	0.34	0.49	0.00	0.22	0.65	0.06	1.00	0.06	0.20	0.66	1.00	0.16	0.84	0.91

8.3 Ranking of technologies in different applications

First, MCDA results for all main criteria are discussed, and total rankings are given at the end. Figure 8-2 provides the results for the aggregation of economic criteria namely; investment cost and life-cycle cost (LCC). The first row of bars represents the optimistic case in which the lower 25% quartiles of MCS results (lower investments and LCC) are used as input for ranking. Main results in the base scenario are indicated in color by the bars in the second row. Finally, the pessimistic scenario is represented by the 75 % quartiles (high investments and LCC).

The first case is represented by ETS which includes CAES and PHS (indicated in yellow and dark-blue) as technologies for comparison reasons. It also represents the principal business case for large bulk storage technologies as already mentioned earlier. LTO and NMC are not included in this case, due to graphical issues (ranking is the same as in the case of HMGS). PHS dominates this application followed by CAES and VRFB. The latter seems to be the most competitive technology in economic terms among battery storage but is followed narrowly by NaNiCl which switches ranks with LFP in the pessimistic scenario. In general, LFP dominates the group of Li-based batteries. NaS and VRLA share the last two ranks. Whereas the first has a close distance to the other technologies and the latter not.

Wind energy support only includes battery storage technologies, which are dominated by NCA and LFP. VRFB and NaNiCl share ranks 3 and 4 and switches ranks in the optimistic case due to their comparable investment cost and LCC. LTO and NaS share the ranks 6 and 7. The first has very high investment cost whereas the latter has a comparably low-efficiency grade resulting in higher energy cost in LCC. Again, VRLA is ranked last.

Results for primary regulation are slightly different to the other two cases. LFP is ranked first, followed by NCA due to their balance of investment cost and LCC. Here, NMC is ranked 3rd followed by NaNiCl and with some distance by LTO. VRLA is ranked in the 6th place as NaS and RFB can be considered as not suitable for this application which comes especially true for NaS. This results from the energy to power ratio of this technology of 6 to 1 which results in a considerable oversizing.

The case of HMGS is calculated for a 3.33 energy to power ratio which favors other technologies then VRFB and NaS which are ranked last due to their comparably low-efficiency grades in combination with high electricity cost resulting from PV and small wind turbines. Thus, VRLA also lose ground to other technologies and are ranked on the 6th rank. Here, LFP and NCA dominate again the application followed by NaNiCl and NMC. It can be seen that the last three ranks can switch within the other scenarios, results should for these thus be seen as critical due to very close results in the different viewed scenarios.

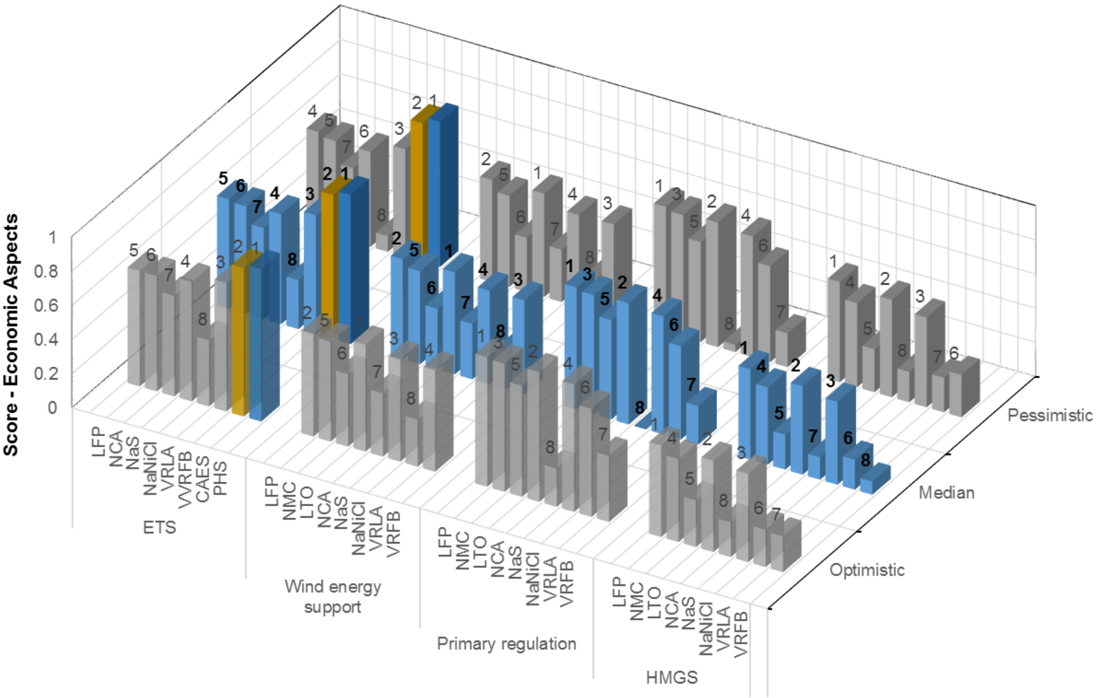


Figure 8-2: Results for economic criteria, all technologies and application areas considering Optimistic, base and pessimistic cases

Aggregated results for environmental criteria on the base of stakeholder weights are given in Figure 8-3. It can be noticed that ranking varies considerably in relation to those obtained for economic criteria. LFP, NCA or LTO share within all application areas despite ETS the ranks one 1 to 3. Ranks can vary slightly in the same range depending of the viewed scenario (optimistic or pessimistic). LTO has a very high cycle life time, resulting in a considerably higher score due to a low number of cell replacements which can be seen in contrast to its rather low economic ranking. Here, PHS is ranked third in the case of ETS and switches ranks with NCA in the optimistic scenario. CAES is ranked last due to the combustion of natural gas.

VRLA is ranked last for wind energy support and HMGS. One exception is the primary regulation application field where NaS has the lowest results, due to its significant oversizing. RFB is ranked lower with higher E/P ratio due to an increasing need for Vanadium Pentoxide which comes especially true for wind energy support (E/P ratio of 10). In general distances among total scores are very close in case of lithium-based technologies and NaNiCl.

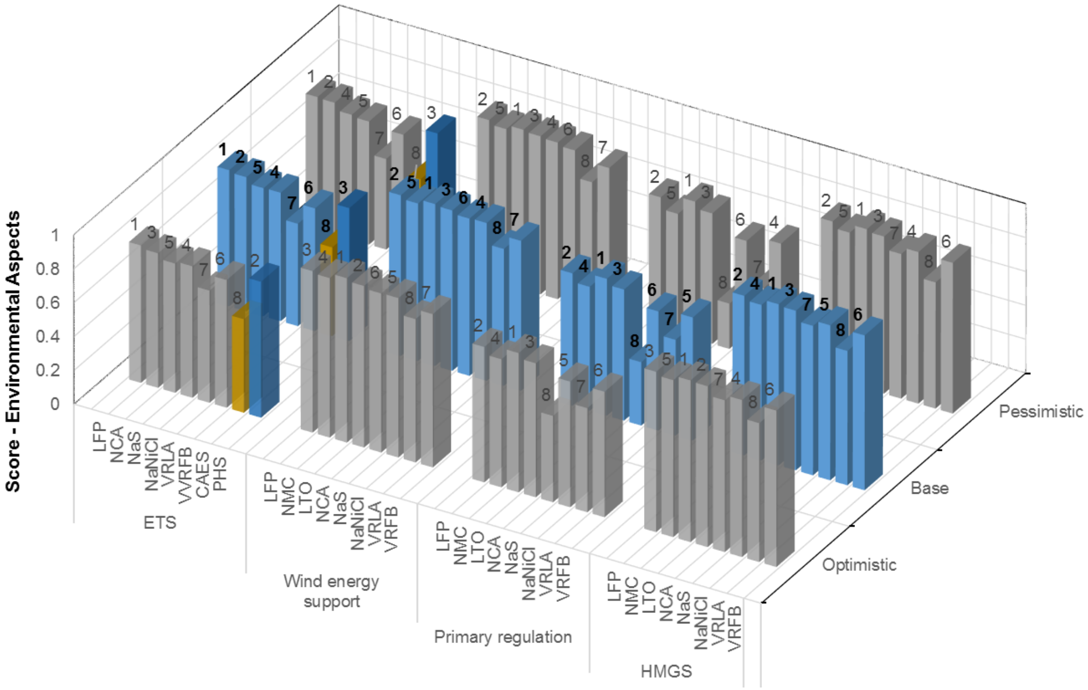


Figure 8-3: Results for environmental criteria, all technologies and application areas considering optimistic, base and pessimistic cases

The results for all technology aspects are summarized in Figure 8-4. These are evaluated independently from application areas as explained in chapter 7. In consequence, only ETS is compared with other application fields as ranks of the latter do not change. Details on the evaluation can be found in the corresponding chapter 8.1.

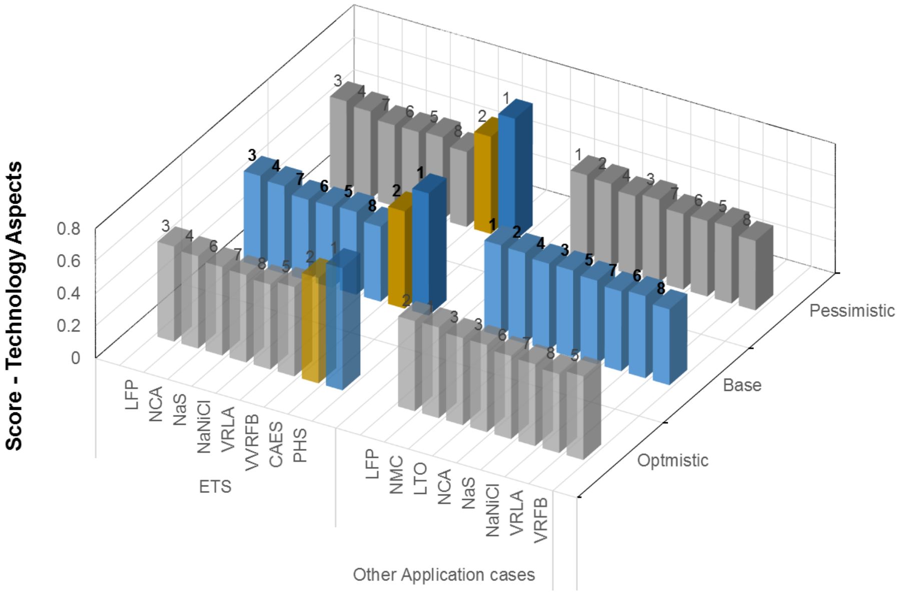


Figure 8-4: Results for technology criteria, all technologies and application areas considering optimistic, base and pessimistic cases – scores do not change for the single application cases and are thus summarized to "other application cases."

ETS includes two different technologies, namely PHS and CAES which dominate the other alternatives due to high cycle and calendric life times. The optimistic case is also characterized by an equal maturity degree of all technologies to receive a pure technology driven picture. This leads to a change of ranks between VRLA and VRFB. Li-Ion based technologies dominate technological aspects in all other application fields due to a good balance of properties of these technologies and a comparably high maturity degree. Again, VRLA and VRFB change ranks in the optimistic case. Admittedly, technological criteria can be seen as redundant as the also have high impacts on LCC and LCA results. Nevertheless, a particular relevance is attributed to them when stakeholders are confronted with them as they are easy to interpret.

All results for the aggregation of social aspects are indicated in Figure 8-5 where only two cases are shown as in the case of technology aspects as ranks do not change in the other application areas. This is a result of the relative bad availability of data in this field and indicates a high demand for further research. It can be seen that PHS has the lowest score of all technologies. This can be mainly explained by the low perceived public acceptance of this technology. It is surprising that CAES is ranked first. A reason for this circumstance it the high score of this technology when it comes to regulatory issues and comparably good score for its perceived acceptance. Battery storage ranks are the same for all applications; only VRLA is ranked higher due to the availability of regulations regarding recycling rates (compare section 7.3.1).

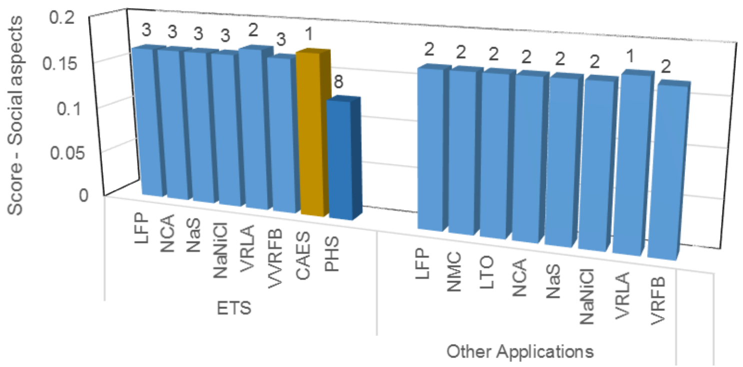


Figure 8-5: Results for social criteria, all technologies and application areas considering optimistic, base and pessimistic cases – scores do not change for the single application cases and are thus summarized to "other application cases."

Total results for all analyzed economic, social, environmental and technological criteria, technologies and application fields are given inFigure 8-6. Aggregation has been carried out by TOPSIS using the weights for the four main criteria provided by AHP (See chapter 6). Again, the structuring of the graph is the same as in the case of the environmental and economic evaluation.

The case of ETS is dominated by PHS, followed by CAES which is interesting as the technology can balance its low score from environmental evaluation with the one form economic evaluation. These two criteria are almost equal ranked, but economic performance of all other battery types is far lower in comparison to considered large-scale energy storage technologies. CAES changes rank with LFP in the optimistic and pessimistic case. Even low acceptance scores of PHS did not omit high ranking of this technology as social aspects were in general ranked very low.

In the three remaining cases, lithium-based technologies despite LTO achieved comparably high ranks, as promising results achieved in the environmental assessment of this technology do not outweigh the low economic score it. NaNiCl shows comparable performance to LIBs due to a good balance of scores. NaS has a rather low ranking (6 to 7), which comes especially true in the case of primary regulation (E/P 1) due to its fixed E/P ratio of 6. The case of RFB is highly dependent on the viewed application field. It can be stated that this technology has, in general, a high potential for large-scale applications with high E/P ratios but not for other areas where lower storage times are required. Results for HMGS should also be seen in the context, that battery size was set to an E/P ratio of 3.33. Higher E/P ratios can lead to changes in ranking which will be part of the following sensitivity analysis. In general, VRLA scores low almost all cases and scenarios, still this technology shows low investment cost and is often used for applications as uninterruptible power supply. It could be however shown that performance of most technologies is dependent on the chosen application area.

The use of different scenarios/datasets does not lead to significant changes in ranking. Only slight changes of up to one rank can be observed (HMGS for NaS in Figure 8-6).

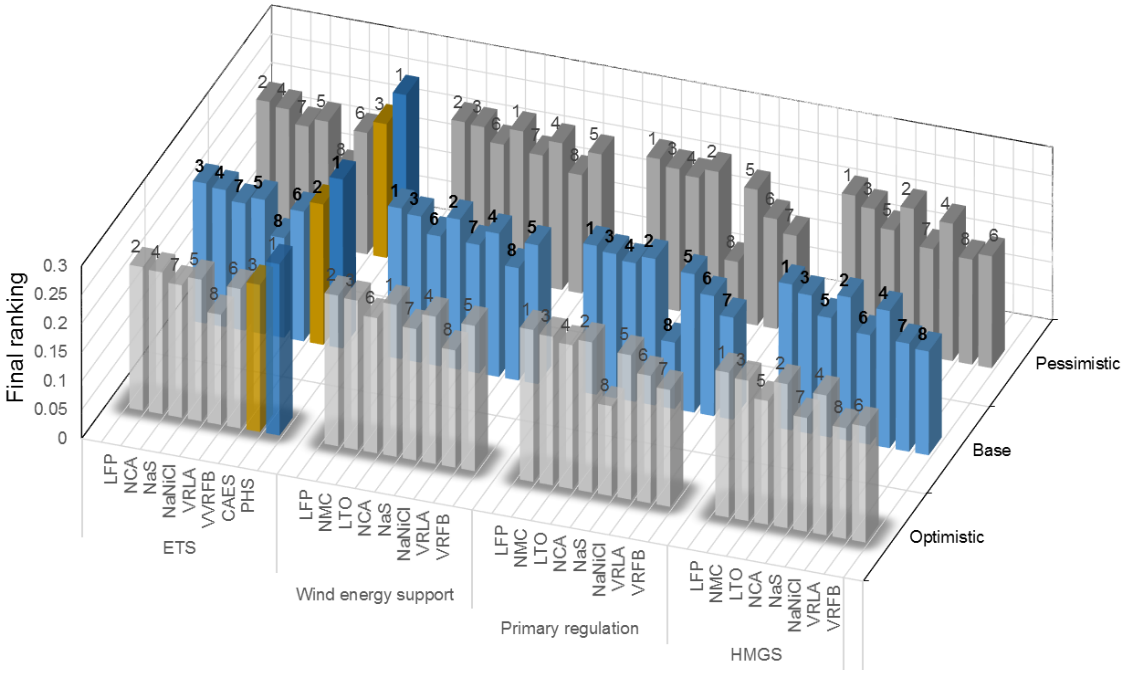


Figure 8-6: Final Results for indicative ranking, all technologies and application areas considering optimistic, base and pessimistic cases –

8.4 Sensitivity analysis for HMGS

The following chapter will give some insights into major parameters which have an impact on the presented results. Firstly, an overview of different modeling assumptions for HMGS as a reference case and their impact on final results is given. In the second section impacts of different AHP rankings are given for selected application cases.

8.4.1 Impact of assumptions: HMGS sensitivity analysis

The application case for HMGS is used as a reference case to explore how changing modeling assumptions impacts final raking of considered technologies. The sensitivity analysis includes 2 different scenarios in relation to the base which are as follows:

A) Improved storage capacity: Storage size is increased from 1 MWh to 2 MWh, whereas cycle probability is maintained (energy to power ratio of 6.66).

B) **Base case:** reference case, see chapter 7.4.2 with 1.4 cycles and 1 MWh storage capacity

C) Low cycles per day: represents the minimum average number of cycles per day (from 1.4 reduced to 0.3) obtained from the HMGS model

The results of the considered scenarios regarding recipe are given in Figure 8-7. It can be seen that changing assumptions regarding the size and operation conditions of storage have an impact on ranking. Increasing storage capacity changes rankings up to one place for most technologies where NCA switches to rank two and NaNiCl and NaS to the 4th and 5th rank. VRFB is rated worse in relation to the base case due to the higher amounts of VO_5 electrolyte required which has a high environmental burden (See chapter 8.3). Decreasing the daily number of cycles from 1.4 to 0.3 has comparable impacts as changing storage size. One exception is VRLA is now on the 6th and RFB on the 8th place. This is due to the reduced amount of exchanges for VRLA which reduces considerably environmental impacts. Using different dataset (optimistic 25 % quartiles, Base median and pessimistic 75 % quartiles) does not have significant impacts on the ranking of the considered technologies (compare with chapter 9.3).

The impacts on economic scores are given in Figure 8-8 and show that there are extreme changes in the ranking of the different battery types. VRFB would be ranked on the 4th place in scenario A) in relation to the base case B) where the latter was ranked last due to reduced investment cost as well as LCC. LTO and VRLA lose ground and are ranked in the last two places. Scenario C) is very favorable for NaNiCl which is now on rank one due to very low LCC. The remaining rankings are comparable to the base case. In total, using different datasets has not led to significant changes in ranking.

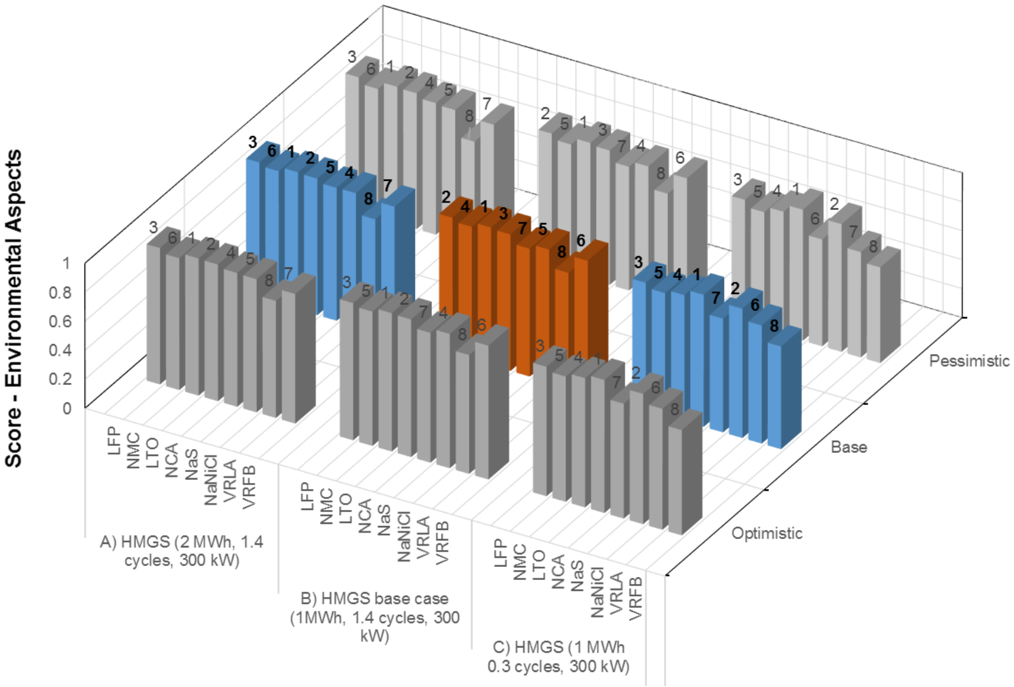


Figure 8-7: Sensitivity analysis of environmental score for the HMGS case with different assumptions on storage size and operation conditions

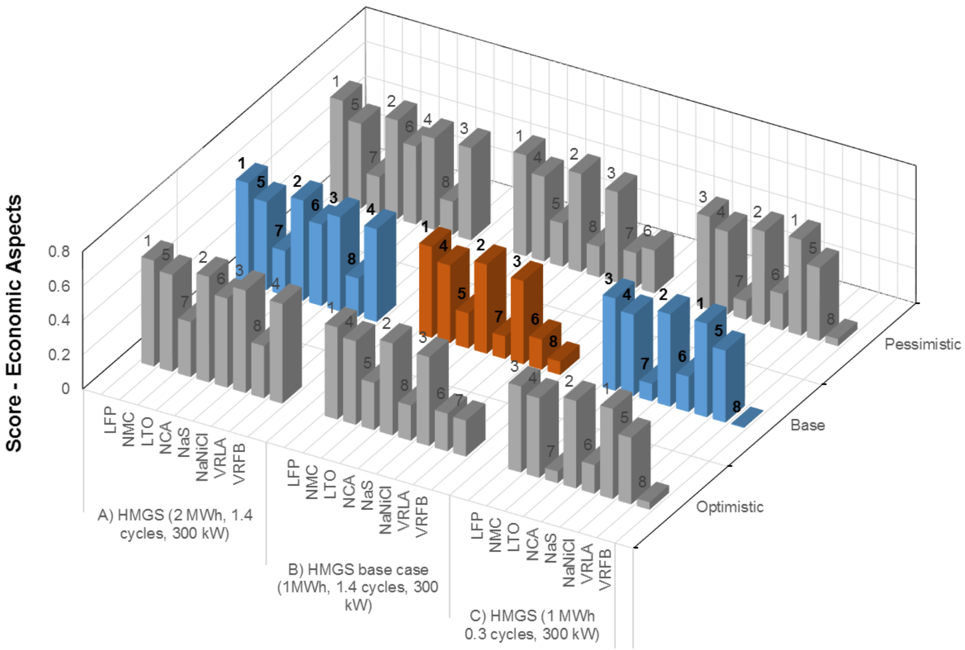


Figure 8-8: Sensitivity analysis of economic score for the HMGS case with different assumptions on storage size and operation conditions

Finally, impacts on total scores are given in Figure 8-9. It can be seen that rankings have a comparable order to the base case where LFP and NCA are always ranked first. VRFB is ranked on the 5th rank in scenario A) and VRLA, as well as LTO last which represents a significant change to case B. Reducing daily cycles leads to an improvement for VRLA which is ranked on the 5th place lower cycling, favors this technology) whereas NaS and RFB remain on the last two ranks.

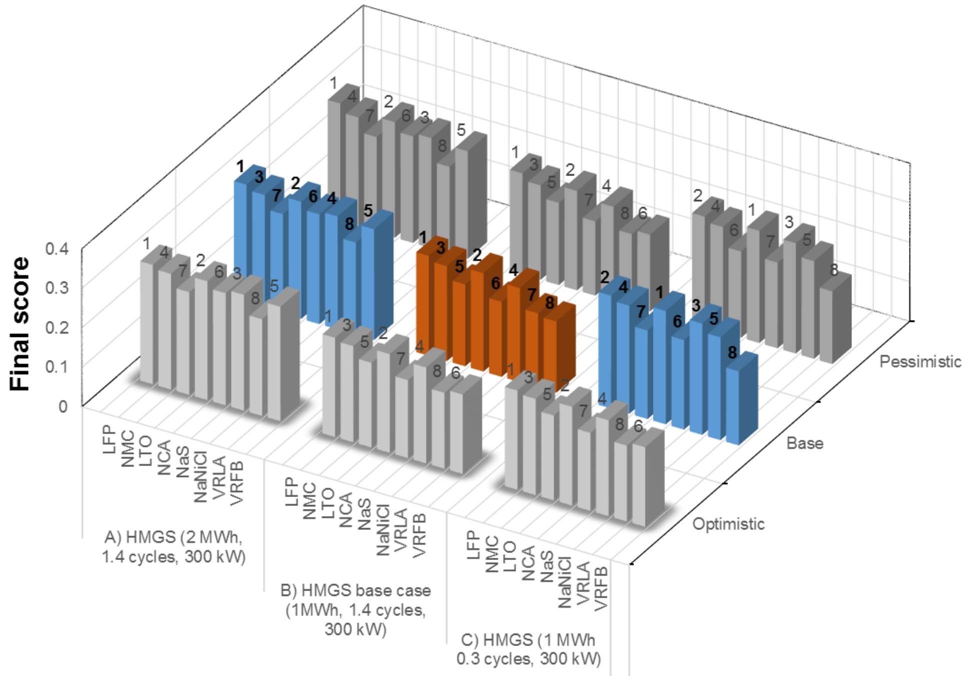


Figure 8-9: Sensitivity analysis related to final scores for the HMGS case with different assumptions on storage size and operation conditions

These changes show that the chosen load profile for HMGS always has to be analyzed for a specific case and that it is difficult to provide a representative case for this application field. In general, assumptions have to be selected carefully, and results should always be seen in the given scenario context.

8.4.2 Impact of changing priorities on technology ranking

A sensitivity analysis for AHP weights is conducted to explore the impact on different preferences on criteria related to the analyzed technologies. All pairwise comparisons are set to equal to avoid inconsistent comparisons where only the parameter of interest is then changed in relation to the others. First, changing weights for main criteria, then for a selection of sub-criteria are analyzed. Median values from the technology evaluation are used for criteria aggregation. The different weights also indicate which technology would be the most suitable out of the perspective of distinctive stakeholder groups.

Figure 8-10 provides an overview of the impact of different preferences regarding environmental aspects vs. economic aspects as these were perceived as the most critical criteria in average by the stakeholders. Final results are plotted in dependence on a varying AHP scale from 9 (Extremely more important, absolute importance where one criterion is favored over another with the highest possible order of affirmation) to 1 (Equal importance where two criteria contribute equally to objectives). Again, it must be noted that all other criteria weights are set to 1, which represents an equal weight. Final results may thus not be identical with the ones presented in chapter 9.3.

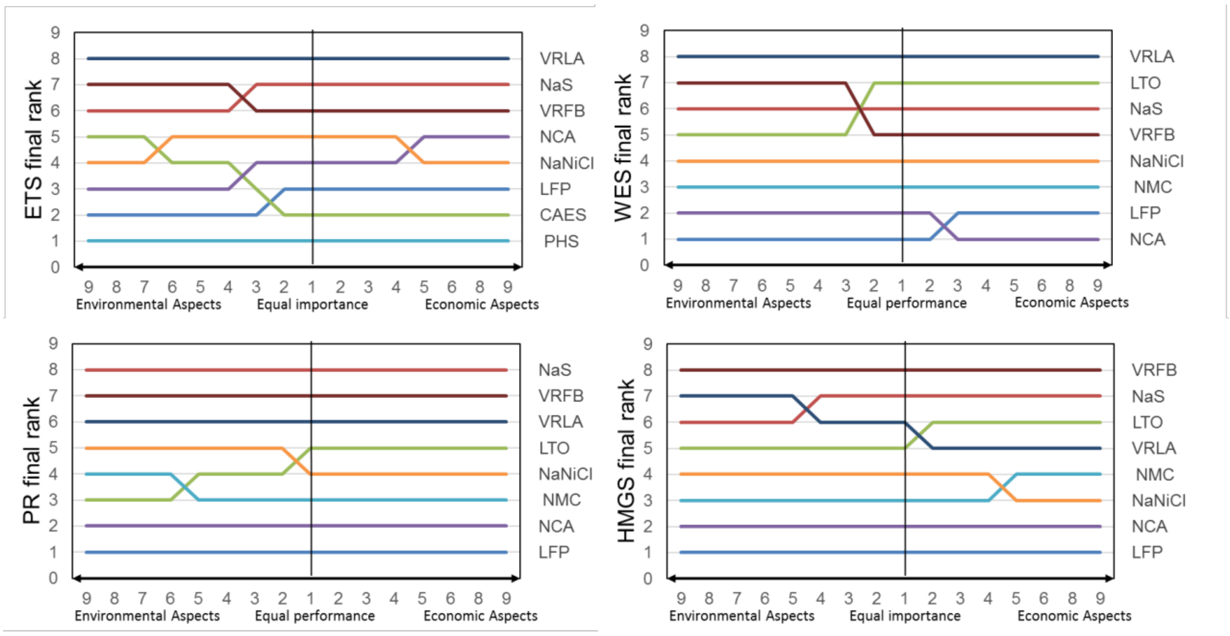


Figure 8-10: Sensitivity analysis for all application cases of varying AHP weights for environmental and economic performance

It can be seen that ranks can change noteworthy depending on the application case and given AHP score up to the maximum of three ranks. The case of ETS shows, e.g., that CAES is ranked on the 5th place when preferences towards environmental aspects are low and on the 2nd rank if a strong economic performance is preferred which correlates well with the results found in chapter 8.5 and 8.6. This is explainable through the strong economic performance of this technology which outweighs its impacts on the environment in case of favorable weighting.

Comparable results are given in the case for WES regarding VRFB with a change from 7th to 6th rank in case of economic preferences. In both cases, VRLA is always ranked last despite different weights. LTO changes ranks in the case of PR, where the technology is ranked 3rd for stronger weights on low environmental impacts and the 5th rank on the contrary case. VRLA, NaS, and RFB are not affected by different weights and remain on the same ranks. The first battery type is ranked on the 7th rank in case of HMGS and a stronger emphasis on environmental criteria and on the 5th rank on the contrary case for economic performance.

Figure 8-11 depicts the impact of changing weights related to technology aspects and environmental vs. social aspects for ETS as there are almost no changes for the other applications observable. CAES changes rank in case of a strong preference towards social aspects as follows: one rank in comparison to technology aspects due to a very low score on acceptance for PHS; 3 ranks in case of lower preferences towards environmental aspects.

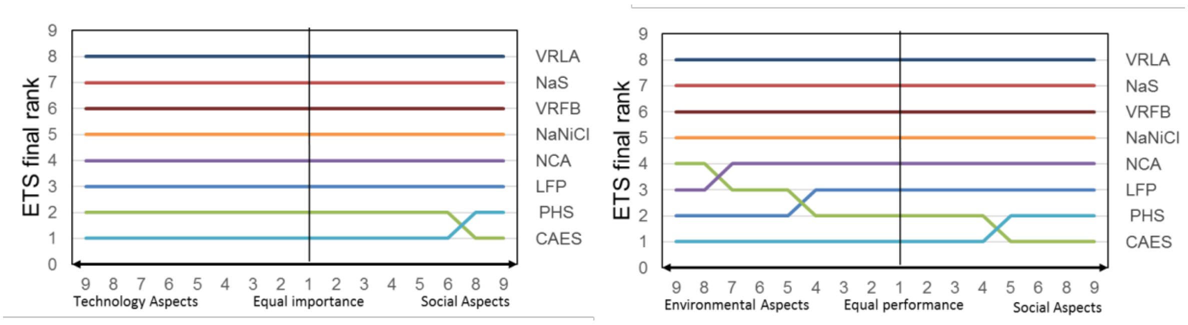


Figure 8-11: Sensitivity analysis for ETS with different AHP weights for technology and environmental aspects vs. social aspects.

It is not possible to provide a sensitivity analysis for all sub-criteria and application cases. The analysis in the following is thus limited on ETS and HMGS and some selected criteria. Weighting the sub-categories differently can lead to a change of maximum 2 ranks as depicted in Figure 8-12 for the case of ETS and HMGS. The upper two graphs show the results for different weights on investment cost vs. LCC. It can be seen, that a preference towards of these two criteria can lead to a switch of ranks for CAES and LCC and that NaNiCl can lose up to two ranks in case of a stronger weight for LCC. The same comes true for VRLA in HMGS where the technology is first ranked on the 6th rank and then on the 8th.

The lower two graphs represent the changes which can occur in case of different attributed weights related to damage to ecosystems and damage to human health for the same application cases. In ETS only CAES and PHS switch ranks. PHS is in total ranked second in case of a higher preference towards low damage on ecosystems due to high impacts related to urban as well as agricultural land occupation and natural land transformation. CAES switches rank with PHS when damage to human health is weighted stronger due to the formation of emission related to the combustion of natural gas (greenhouse gases, ozone depletion, etc.). Comparable results can be seen for the case of VRLA due to the use of lead (88% share) which has a high impact on human health.

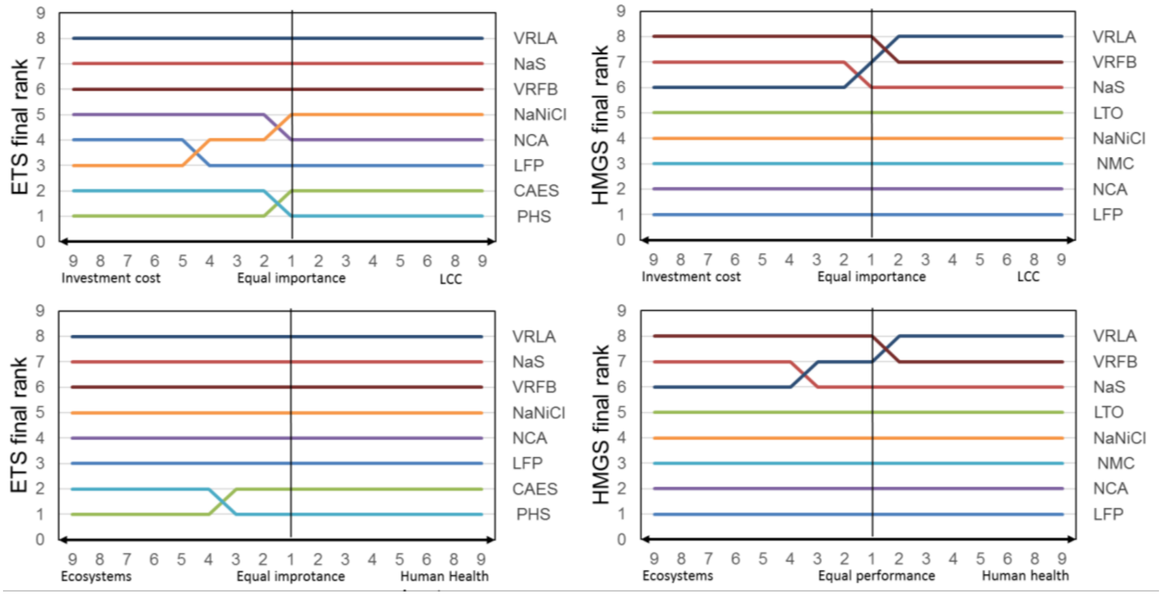


Figure 8-12: Excerpt of the sensitivity analysis for ETS and HMGS with varying AHP weights for the sub-criteria investment cost vs. LCC and damage to ecosystems vs. human health

8.5 Summary and discussion of results

Table 8-4 provides an overview of given stakeholder preferences, their calculation, and sharedness among the participants regarding the main criteria. Green indicates a strong preference and a high consensus, a weak preference and low consensus are indicated in red, intermediate results are depicted in yellow and orange. Enactors attributed priorities within their enactment frame with a strong tendency towards economic aspects (LCC) and technology performance of electrochemical energy storage. Impacts on the environment and social aspects seem to play a minor role for them. Selectors have a broader view with a strong focus on environmental issues and comparably equal priorities for the other factor. Combined views from enactors and selectors within the frame of CTA allow it to shift the loci of assessment to provide a broader picture about the relevance of properties regarding “better” technology.

Total priorities have a stronger orientation towards the environment and economic factors, followed by technical and social aspects for both groups. The consensus of all participants regarding the importance of all used criteria was rather low. Single group consensus was the highest for enactors for main criteria (54%) in relation to selectors (40%). An explanation here for might be that the actors of the latter group are more heterogeneous in relation to the first. On average, all participants perceived the economic and environmental performance as most important (0.241 and 0.236). Technology performance and social aspects are comparably ranked lower (0.197 and 0.131). The consensus (0 none, 50% low and 100% total consensus) on the importance of different criteria with a value of 42% can be considered as low which also comes true for all sub-criteria with scores below 38% (See chapter 8.2 and table 8.1). Interestingly both groups (enactors and selectors) have comparable tendencies regarding priorities attributed to the different sub-criteria.

The low consensus about the importance of the two sub-criteria LCC and Investment cost was surprising, especially as it was expected that consensus would be high. Investment costs play a higher role in short-term investment strategies. In contrary LCC plays a stronger role when it comes to mid- to long term investments and has a broader aim (the entire life cycle). Both criteria are to a certain degree redundant when calculated but not regarding decision making which is at the end always based on a company's preference.

Table 8-4: Summary of weights for main criteria and related consensus for enactors, selectors and combination of both (total) (green = high; Orange= moderate; red=low)

	Attributed weights [-]			**Consensus about weights in [%]**		
	Enactors	Selectors	Total	Enactors	Selectors	Total
Social & Political aspects	0.112	0.149	0.131	12	41	34.3
Techn. Performance	0.237	0.162	0.197	25	40	32.9
Env. impacts	0.136	0.252	0.236	14	65	37.9
Economic perf.	0.373	0.167	0.241	0	2	0

All priorities are used for criteria aggregation in combination with four different application cases (hybrid microgrid generation (HMGS), energy times shift (ETS), primary regulation (PR) and wind energy support (WES)) to pick the "best" or most sustainable energy storage alternative. An overview about the indicative ranking of (electrochemical) energy storage technologies for the four different cases of ETS, RS, PR, and HMGS is given in Table 8-5. Additionally, primary positive and negative influence variables on the final ranking are also indicated in the same table.

It could be shown that batteries are ranked behind PHS and CAES in case of bulk storage applications as ETS. This is highly interesting as CAES scored apparently the lowest in the category of environmental impact, but second in economic and technical performance. PHS achieved the lowest score for social aspects, but its high economic score has balanced out this drawback. The VRFB achieved the highest score among all battery types in economic terms for ETS, but low results in environmental criteria lead to a slightly low ranking (6 of 8). The use of batteries in this application would make only sense in case of the absence of infrastructure required for alternatives or a high environmental preference (at least when compared to CAES).

The other applications are strongly dominated by either LFP, NMC or NCA and NaNiCl. The performance of VRFB and NaS is highly dependent on the considered E/P ratio. A high E/P ratio leads to a better ranking of these technologies. Nevertheless, Li-ion based technologies dominate them in all cases regarding total scores. The use of different MCDA evaluation "scenarios" using lower and upper quartiles as well as median values has only low impacts on the final rankings (max. 1 rank). The sensitivity analysis has shown that depending on the application case efficiency grades can have a high impact on LCC as well as LCA results for all battery types. Calendar life time has proven to have only little impact impact in relation to cycle life times as they determine battery exchange rates in most cases. These results can be seen as contradictory to the weights attributed by stakeholders to calendar life time and efficiency within the survey (see chapter 7.2.1). Additionally, the sensitivity analysis shows clearly that technology only changes up to three ranks depending on the viewed case and the attributed (extreme) weights. Variation of priorities related to sub-criteria can lead to changes of up to 2 ranks. Changing major assumptions in the reference case of HMGS has also led to a maximum change of up to 3 ranks. In total MCDA results can be considered as relatively robust regarding the conducted sensitivity analysis.

It has to be stressed that presented rankings should not be seen as an end of state, rather as indicative. They can provide a first base for actors to discuss implications leading to these results and to improve specific technologies into a certain direction.

Table 8-5: Summary of technology ranking within the four considered different application cases (green = high rank; Orange=average rank; red=low rank) and major issues identified related to specific technologies

	Indicative Ranking				Major positive and negative impacts	
Appli.	**1 HMGS**	**2 WES**	**3 PR**	**4[1] ETS**	**Positive**	**Negative**
LFP	1	1	1	3	Life time, env. impact	Cost, recycling unclear[2]
NCA	2	2	2	4	Efficiency, life time, env. impact	Cal. Life time
LTO[1]	5	5	4	-	Efficiency, env. impact	Cost, energy dens.
NMC[1]	3	3	3	-	Efficiency	Cost
NaS	6	7	8	7	Cost	Efficiency, env. impact
NaNiCl	4	4	5	5	Cost, env. impact	Life time
VRLA	7	8	6	8	Recycling, inv. cost	Efficiency, env. impact
VRFB	8	5	7	6	Life time, cost	Efficiency, env. impact[3]
CAES	-	-	-	2	Cost, life time	Env. impact, efficiency
PHS	-	-	-	1	Cost, life time	Social acceptance

1: LTO and NMC are not evaluated in this field, as already two Li-based technologies are included
2: comes true for all Li-based systems
3: has to be validated

9 Conclusion

This work has the aim to identify the drivers and the future role of different stationary battery storage technologies within the German energy transition and to pick the "best" or "better" technology alternatives using a Constructive Technology Assessment (CTA) oriented framework. Providing "*better technology in a better society*" is postulated as a goal within CTA-literature. The goal remains on purpose loose and does not provide a recipe or definition of what "better" signifies. CTA provides a way to think through the future we want to achieve by reducing potential negative impacts co-produced through the interplay of society and technology (may it be environmental impacts, stranded costs or acceptance problems). It offers a space to broaden perspectives, increase reflexivity and to enable social learning among actors. These attempts are closely connected to some discussions in the field of sustainability which is often named in line with "better" technology (see chapter 3.3). However, CTA does not necessarily aim to provide a sustainability assessment of technology it rather aims to contribute to the realization of better technology as stated before. This CTA framed work uses criteria named in literature in line with sustainability to provide a first base to explore actor visions and expectations (see chapter 3.3 and 3.4) on battery storage using a transdisciplinary approach tailored in light of CTA theory (see chapter 4).

The central question raised is broken down into 4 sub-topics (compare sub-research questions in chapter 4.2) which are discussed in line with CTA theory. First general expectations and visions about the future role of battery storage as a flexibility option are summarized, and recommendations are provided within a SWOT analysis. Then, secondly, expectations related to an optimum construct of battery storage are highlighted using the AHP. Thirdly, impacts of these expectations and a indicative ranking of "best" technologies are presented in a quantitative way (LCA, LCC, and TOPSIS). Recommendations of how to open and to provide a broader base for decision-making and technology design are given in the fourth section of this chapter. Additionally, some research recommendations for systems analysis are also provided. Finally, a critical reflection on the development and realization of this research including CTA and the used modeling methods is given.

9.1 Future role of battery storage technologies

The first question block is based on the literature review as well as stakeholder expectations and visions in chapter 2 and 5. It is considered about the general role of battery storage within the German energy turnover, its role among other flexibility options and related main driving forces and obstacles. And, to identify new linkages between a range of aspects business models and potential system integration levels of battery storage.

It can be concluded that there is nothing as a most "probable scenario" for battery storage market diffusion and use, the work provides instead an overlaying narrative and major implications based on stakeholder expectations and visions which can serve as a base to further explore potential battery technology trajectories (compare chapter 5).

Chapter 2 and 5 have shown that market diffusion of energy storage technologies is seen as heavily dependent on the share of RES, available (or absent) regulations and market conditions. Energy storage technologies are considered as one balancing option among others which are namely; 1) Grid reinforcement measures, 2) flexible demand, 3) flexible power plants and at the end of the line 4) electric energy storage which itself is separated into modular and centralized storage. Stakeholders believe that the energy transition will only be successful through an interplay of all these technologies.

A comparable high relevance is attributed to battery systems among other flexibility options in the online survey. Interestingly, interviewed experts perceive battery storage as one of the most expensive technologies and don´t attribute them a high relevance in the next 10 years to come. Market diffusion of electrochemical storage is believed to happen in line with increasing decentralization of the grid and further progress in electric mobility (see chapter 5.4.2). Stakeholders agreed that it is hard to make estimations about the uptake of battery energy storage technologies due to missing business cases and regulatory frameworks. In general, electricity markets nowadays do not value the services provided by energy storage technologies which is seen as one of the leading barriers for market penetration by actors. The stacking of services through the integration of multiple business cases is considered as promising for a more efficient use of battery technologies. It is believed that battery storage will be profitable within an application range of seconds to days, mainly on a decentralized and generation near level as soon as prices further decrease (see chapter 5.5.1).

However, most important single applications for battery storage named by stakeholders and used for the technology evaluation are:

- **Decentralized storage:** Storage nearby demand in combination with PV or wind turbines
- **Generation near energy storage:** Only in combination with RES as wind
- **Short-term balancing**: Provide several balancing services
- **Day-ahead business:** Participation in ¼ h spot markets

Especially decentralized energy storage and short-term balancing were mentioned as highly promising areas for battery storage.

The most critical technology properties for stationary applications named and ranked by experts are cycle and calendric life time, followed by power density, efficiency and recycling abilities with energy density on the last rank. Further discussion about battery storage with stakeholders was structured mainly around 5 topics already identified preliminary in the literature (see chapter 2.8.3), technology, economics, environment, application possibilities and social factors. Table 9-1 provides a summary of stakeholder expectations and visions in the form of a SWOT analysis of endogenous threats, opportunities and indigenous technology strengths and weaknesses and potential strategies derived from interviews to tackle named issues.

9.2 Expectations on battery energy storage properties

The second theme block with corresponding sub-questions is concerned about the demands and expectations related to an optimum construct of battery storage technologies considering different actor expectations (namely enactors and selectors) regarding (sustainability) key parameters; and the “sharedness” of these expectations. Eleven sub-criteria were identified in orientation to MCDA and sustainability literature and structured around four main criteria namely; economic as well as technical performance, environmental impacts and social & political aspects. Chapter 2 showed that most studies considered in the MCDA literature review focus on sustainability criteria of different flexibility options and are deemed to be insufficient due to a unilateral perspective (no consideration of different actor groups) and the absence of providing anything as social learning.

Table 9-1: Summary and SWOT-Analysis of electrochemical energy storage technologies for stationary applications including different strategies (Strength-opportunity-SO, strength-threat=ST, weakness-opportunity=WO and weaknesses-threat=WT strategies) based on expert visions and expectations as well as literature used in chapter 2

Endogenous Aspects **Technology aspects**	**Opportunities:** 1. Scale effects (electric mobility) 2. Improvement of production 3. Decentralization / new business models 4. Perceived high local acceptance	**Threats:** 1. Limited knowledge (DoD vs. cycle life time) 2. Which technology into which business case? 3. Competing technologies (DSM, flex. power plants) 4. Missing regulation 5. Environmental doubts
Strength: 1. Several technologies available 2. High efficiency (for most) 3. Modularity 4. Fast response times	**SO-Strategies:** A) Use wide application potential B) Adapt to new market situations (modularity) C)	**ST-Strategies:** A) More demonstration projects B) Increase life time C) Develop proper SoC management systems
Weaknesses: 1. Cost (up front) 2. Life time issues 3. Pot. toxic materials 4. Environmental dangers	**WO-Strategies:** A) Find suitable business models B) SoC-cycle management C) Risk management, monitoring D) Optimization of cell manufacturing	**WT-Strategies:** A) Opt. of operation modes B) Prove operation in appl. C) Increase recycling rates, risk management

Referring to the survey selectors and enactors agree that sustainability should play a stronger role in the development and investment of new flexibility options. Interview participants see sustainability instead as a normative and blurry goal, not relevant nowadays but in the future.

The AHP was identified to be a suitable and easy to realize method to explore normative expectations about desired technology properties and was included in the conducted survey. A preposition of this work is that the higher the degree of shared opinions about a criterion is, the more probable it becomes that stakeholders act accordingly to these expectations (compare chapter 3.4). The latter can thus inspire development and the related trajectory of new technological developments. Using the AHP and calculating the consensus helps to quantitatively gather expectations about how technology should ideally look like and if these impressions are shared among the addressed community. These expectations are sought to inspire sustainable or “better” technology development, span up potential trajectories and to serve as a base for further discussions.

One of the highlights of this research is the proof that expectations about technology characteristics are settled within concentric perspectives. Indeed, enactors have a strong orientation towards economic and technological performance criteria which reflects the concentric bias of this group (developing the product right and to look at economic factors and market situation) named in CTA literature. These preferences are also shared to a certain degree among this “insider” group (see chapter 8.2). Environmental and public concerns (if there are any regarding battery storage) are rather seen as something to overcome to make a technology marketable. This impression is reinforced through interview results where environmental impacts and acceptance are considered as something that could slow down project development (see chapter 5.4.4). It becomes fortuitous if outcomes generated through the consultation of this group will be optimal regarding the goal of creating better technology.

Selectors provided a more diverse picture and have a stronger focus on other comparative criteria which is again nicely in line with CTA literature. Especially the aspect of low environmental impacts is considered as highly relevant for this group. Economic, technological and social factors are rated in a quite balanced way. Consensus towards the relevance of main criteria is very low within this highly diverse group and indicates that there is a high potential for further discussion about criteria relevance. However, selector preferences are to a certain degree opposing enactors expectations on the relevance of (electrochemical) energy storage technology characteristics. Confronting the latter with more diverse selector notions is assumed to provide a first base to broaden perspectives on technology development and selection processes.

Combined views from enactors and selectors within the frame of CTA allow it to shift the loci of assessment to provide a broader picture about the relevance of properties regarding “better” technology (see section 3.5). The combination results in a more balanced view on the importance of different technology properties. Nevertheless, economic and environmental criteria are in total considered as more significant in relation to technology or social based criteria (see chapter 8.5). Especially in case of the latter actors struggled to attribute weights as they considered them as too fuzzy. In the end, there are no collective or only low shared opinions among actors regarding the diffuse goals of, e.g. lowering environmental impacts and increasing economic performance. This may be explainable through the different interpretation of criteria through participants and the unguided way of elicitation in the form of an online survey. There is thus more effort required to create a broad consensus to provide a base for agenda building and further actions through a more participative platform.

9.3 Technology evaluation & picking the “best” alternative

Naturally, implications for technology evaluation arise through the predefinition of criteria within the MCDA-process as different system analysis models must be fitted and found accordingly to these (see section 4.4 and 6). In general MCDA in combination with interviews, LCA and LCC proved to be highly useful to quantitatively explore impacts of actor expectations and visions and to determine which technology performs best in the face of these including potential implications for further technology development (see table 8.5).

Chapter 5 has shown that main concerns of stakeholders are related to daily operation cycles and depth of discharge and their impact on overall battery life time and resulting cost. These issues were adopted in the LCC and LCA model. Representative battery technologies identified in the literature review and analyzed in this work are various lithium-ion batteries (LFP, NCA, NMC, and LTO), valve-regulated lead-acid batteries (VRLA), high-temperature batteries (NaNiCl and NaS), and vanadium-redox-flow batteries (VRFB). Additionally, compressed air energy storage (CAES) or pumped hydro storage are included in one application scenario for comparison reasons. The comparison of this technologies on the base of the defined criteria within AHP was carried out for 4 representative applications fields in orientation to those named by stakeholders in section 9.2. Simplified load profiles have been defined to quantify impacts on the base of literature and own modeling as follows:

- **1 Storage for Hybrid-Micro-Grids** (HMGS) **–** optimization model (see section 7.4.2)
- **2) Wind energy support** (WES) **–** increase arbitrage possibilities of direct wind marketing
- **3) Primary regulation** (PR) – short-term balancing
- **4) Energy time shift** (ETS) - comparison with CAES and PHS

Referring to the interviews, decentralized storage (HMGS) and short-term applications (PR) are seen as most promising areas for battery storage. The first is used as a reference case for sensitivity analysis within technology evaluation using an own HMGS model for load profile generation.

PHS and CAES as typical bulk storage technologies are ranked first in case 4 (ETS) due to the poor economic performance and missing maturity of most battery technologies. Interestingly several battery technologies achieved promising scores regarding environmental and social criteria but could not outweigh comparable low performance in other named areas (especially economics). VRLA and NaS are ranked last in all cases because of relatively low efficiencies and cycle life times. Ranking of VRFB is highly dependent on the considered use case and is favored by high energy to power ratios. Li-Ion batteries have proven to be the most recommendable technology among other electrochemical energy storage technologies for most application areas in economic and environmental terms.

In general, the suitability of a technology for a particular business case should be tailored thoroughly in every case as it is not possible to provide an ultimate ranking. This is shown through sensitivity analyses conducted for HMGS by changing some of the underlying assumptions (storage capacity, daily operation cycles, etc.) which has led to stronger changes in final rankings (see sensitivity analysis in section 8.4.1). Additionally, it was not possible to include recycling of technologies which might also have a certain impact on LCC and LCA and thus technology ranking through the re-use of specific materials. The sensitivity analysis in section 8.4.2 showed that rankings remain relatively robust in the face of weight variation (max. 3 ranks).

Rankings should thus not be seen as a final state but as an indicative base for further discussion about technology impacts, use, and design in face of sustainability. The low scores of some technologies do not indicate that they are "non-sustainable" or worse than other options per se, instead that other applications can be found for them and that properties of technologies should be improved through corresponding research efforts (see section 8.5 Table 8-5). A question which remains is how to use these results to achieve anticipation, reflexivity and social learning which remains a theoretical task in this work as discussed in the following chapter.

9.4 Providing a base for stakeholder modulation and future research

Literature review about MCDA has shown that there is an absence of approaches that enable social learning on multiple levels between different actors when it comes to technology selection and development. The presented methodology is seen as suitable to enable social learning and reflexivity through the quantification of expectations and to provide a broader as well as a robust basis for decision making and “better” technology design or selection.

Discussing the choice of criteria and attributed weights to these can be considered as a reassessment of perceptions about technology design. MCDA allows it to grasp multiple differences in perceptions, attitudes, judgments, and practices of various actors and to quantify these. In this sense, it provides a solid base for stakeholder modulation following the principles of CTA by allowing differences in opinions to develop a best construct of technology and to make expectations transparent and debatable. And, to confront developers with the numeric dimensions of selector expectations and their consequences to broaden perspectives and increase reflexivity (see chapter 3.5) through, e.g. the indicative ranking of different (electrochemical) energy storage technologies in the face of conducted weights and different application areas. Intermediate results also may provide indicators for developers about aspects that may influence the success (or in this case ranking) of their technology (e.g., certain environmental or economic impacts).

It was not possible to provide a more interactive platform as part of a comprehensive CTA study for this discussion, but an ideal constellation of an extended research framework based on the one presented in 4.4 and recommendations found in the literature (see section 3.5) is given in Figure 9-1. Such an approach should include an interactive workshop to define common criteria, conduct weighting and directly discuss these. It is recommended to test if CTA measures have been fruitful by, e.g. conducting follow-up interviews after a certain time span (e.g. 10 months). In general, it appears that actors are willing to participate in such a workshop and to a lower degree in related follow-up interviews (see chapter 5.3). However, these steps remain a task of future research.

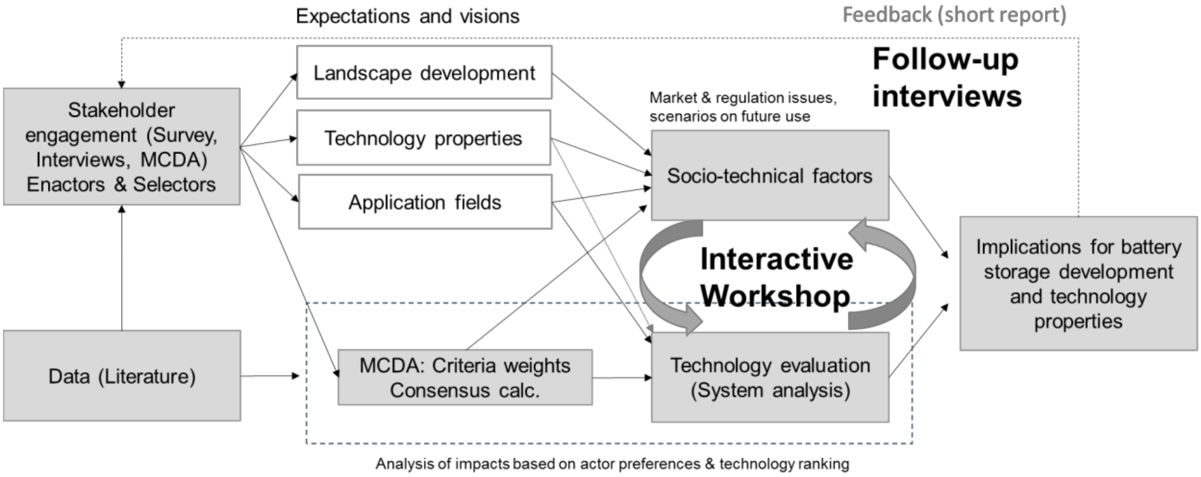


Figure 9-1: Enhancement of the proposed research framework for future assessments

There are several future research potentials for systems analysis of electrochemical storage already adressed in the corresponding chapter 7. Only the most critical ones are named in the following. LCA (and LCC) results for VRFB, NaS and VRLA should be taken with care due to the poor availability of up to date LCI´s. It is thus recommended to analyze these technologies using an originary LCI which was not possible in the frame of this work. It has also to be mentioned, that considering recycling potentials and disposal of the considered battery storage systems may have a significant impact on LCA results. The end of life phase should thus be analysed in more detail in future research.

Additionally, only a limited set of energy storage technologies has been analyzed and discussed in this work. Other flexibility options as the use of hydrogen, flexible power plants, vehicle to grid or power to X should be considered in future assessments.

9.5 Discussion of the conducted research

The underlying philosophy of CTA, as presented in chapter 3 is to provide “better” technology for a “better society” which can be seen as implicitly equivalent to sustainable development. And, to stimulate anticipation, learning, and reflexivity of enactors. It can be questioned if developing socio-technical scenarios as a method are sufficient in every case to prove any kind of positive or negative effects of technology or to contribute to its better socio-technical embedment. As stated in the beginning, this research has a specific explorative character and aims to provide recommendations to conduct a comprehensive CTA study in combination with quantitative system analysis methods (see chapter 4.3.2).

The overlaying narrative found shows how uncertain and complex the development of new electrochemical energy storage is. It is believed that the presented research framework and results can provide a fruitful base to broaden the perspective of related actors and to make them more reflexive by directly providing them insights into consequences of their choices if presented within a workshop. The aspect of reflexibility turned out to be an essential addendum to the conducted MCDA and related system analysis. “Typical” system analysis methods as LCA and LCC to quantitatively assess impacts of technology are highly dependent on data (e.g., inputs as energy consumption, raw materials, ancillary, physical or required operation conditions, life time, maintenance, cost, etc.) and time-consuming (see chapter 7). Most assessments in this field start with extrapolation of available data into the future by the development of scenarios (e.g., as in this work combination of learning curves, economies of scale, linear upscaling with data from comparable mature systems) through the analyst. Such scenarios have to be developed carefully and have to deal with the high uncertainty of data and its poor availability. Complex system analyses as LCA, LCC of emerging technologies thus often require assumptions (ad hoc suppositions) and simplifications (e.g., ceteris paribus conditions). Not considering recycling processes for battery storage technologies is clearly a good example for such a simplification in case of this work.

The articulation of extrapolations and “dynamics as usual” is also problematic as (energy) markets evolve. At the end, only a narrow view of an emerging (battery) technology might be given caused by technological and economic realities and individual ideologies which are implicitly embedded in the modeling apparatus. Such a narrow view might creep in when system boundaries are set up due to practical reasons (see chapter 4.3.2). And, the danger that a CTA researcher might subtly fall into a concentric bias together with enactors. It is believed that the “master narrative” in combination with the conducted MCDA helped to omit this at least to a certain degree.

The weighting of criteria and sub-criteria within AHP allows grasping different perspectives and interests of various stakeholders namely enactors and selectors embedded in different socio-technical sub-regimes making them transparent and debatable. Using AHP helped (at least in this case) to recognize the different roles of stakeholders in different regimes (increase reflexivity as one CTA goal) and to find a common base for further discussion to seek for alignment. Furthermore, AHP provides reproducible insights and allows to grasp strategic intelligence about normative expectation on technology design in the face of different applications scenarios (e.g., different business cases). It has to be mentioned that one has to consider the drawbacks of AHP as, e.g., rank reversal or the domination of a single criterion over other ones. In general, choosing the most suitable MCDA method is a challenging task and should be conducted carefully for every task.

Carrying out a comprehensive CTA exercise using the proposed research framework is a time-consuming task and has to be prepared cautiously. The combination of named system analysis methods under the frame of CTA makes only sense if there are sufficient data and time available allowing it to quantitatively evaluate the technology in scope which is not always possible. Using system analysis under the frame of CTA offers the potential to provide a broader and more robust base to identify, explore and frame potential roles and to identify or minimize potential impacts of emerging technologies within large sociotechnical landscape changes as the German energy transition. Developing socio-technical scenarios might be more adequate in cases where only pure technology concepts are available or in case of the absence of any reliable technical data.

Clearly, time and resources were too short to conduct a more comprehensive CTA approach wherein social learning could be provided in a more participative way as in the form of a workshop instead of sending a final report. This also comes true for the validation of such potential effects (compare chapter 9.4) which remain a task for future research. Nevertheless, following CTA principles helped to break through typical enactment cycles by shifting the locus of assessment towards a broader perspective (also for the LCA or LCC analyst himself). More importantly regarding social learning, results confront *enactors* with the visions, interests, and expectations of *comparative selectors,* and vice versa are believed to create new knowledge of how to develop “*better technology in a better society*.”

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Baumann, M. Zimmermann, B. Peters, J. Weil, M. Chibeles-Martins, N.; Environmental performance of Li-ion batteries for direct marketing of wind power – intermediate results Poster · May 2017 05/2017, , At: Trondheim, Norway, Conference: 11th Society and Materials International Conference (SAM 11)

Baumann, M.; Weil, M.; Moniz, A. Brandão; Hauser, Chr. Sustainability of energy storage technologies. A concept for a life cycle orientated constructive technology assessment. Posterpräsentation auf der 4th International Conference on Sustainability Transitions - IST 2013. Zürich, Schweiz, 18.-21.06.2013. - Book of Extended Abstracts

Baumann, M.; Zimmermann, B.; Weil, M.; 2013, Probabilistische life cycle costs elektrochemischer Energiespeichertechnologien auf Basis eines deterministischen Vollkostenmodells. Posterpräsentation im Wissenschaftszentrum Bonn "Energiewende - zwischen Konzept und Umsetzung". Bonn, 03.-04.06.2013

Peters, F. Fulton J.; Baumann M., Weil M.; Life Cycle Cost Model for Vanadium Redox Flow Batteries; Poster · May 2017 05/2017, Conference: 11th Society and Materials International Conference (SAM 11)

Poncette, D.; Baumann, M.; Wagner, C.; Patyk, A.; Pfeifer, P. Simulation of a CSP-powered hybrid storage network. Posterpräsentation auf der 9th International Renewable Energy Storage Conference (IRES) 2015, Düsseldorf, 09.-11.03.2015

Others (working papers):

Baumann, M. A constructive technology assessment of stationary energy storage systems - A prospective life cycle orientated analysis. Lissabon, Portugal: Universidade Nova de Lisboa, Faculty of Science and Technology 2013 - WPS01/2013 ISBN 1646-8929 (IET Working Papers Series)

Baumann, M**.** Analysis of a controversial decision process: The case of the pumped hydro storage power plant Atdorf in Germany. Lissabon, Portugal: Universidade Nova de Lisboa, Faculty of Science and Technology 2015 - WPS04/2015 ISBN 1646-8929 (IET Working Papers Series)

Baumann, M. Historic and potential technology transition paths of grid battery storage: Co-evolution of energy grid, electric mobility and batteries. Lissabon, Portugal: Universidade Nova de Lisboa, Faculty of Science and Technology 2015 - WPS02/2015 ISBN 1646-8929 (IET Working Papers Series)

CV

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Current position:

Since Jan. 2012-: Researcher (full time) at the Institute for Technology Assessment and Systems Analyses (ITAS) / Karlsruhe Institute of Technology (KIT). Research area: Electrochemical energy storage, techno-economic modeling and life cycle assessment.

Research experience:

Since Sept. 2015: KIT-ITAS, Helmholtz Association Project Energy System 2050 – "*A Contribution of the Research Field Energy"* - Identification of technical and scientific, ecological, economic, and social aspects of energy storage within the German energy transformation.

Since Jan. 2013: CICS.NOVA Lisbon, Member of *CICS.NOVA* - Centro de Estudos de Sociologia da Universidade Nova de Lisboa and Observatório de Avaliação de Tecnologia.

Jan. 2012 – Dec. 2016: KIT-ITAS, Helmholtz Portfolio project*: "Electrochemical energy storage in the system – reliability and integration"* - / Techno-economic analyses, life cycle assessment.

Nov. 2010- March 2011: Laboratório Nacional de Energia e Geologia (LNEG), Erasmus research internship, working area: "*Technical and economic viability of H2 production by biomass gasification with and without CCS*".

Education:

Dec. 2012 –January 2018: PhD student– Nova Universidade de Lisboa (UNL); Faculdade de Ciências e Tecnologia (FCT). PhD-program for technology assessment; Title of PhD: "*Battery storage systems as balancing option in intermittent renewable energy systems–A transdisciplinary approach under the frame of Constructive Technology Assessment*" - Supervisor: Dr.-Ing.: Marcel Weil (ITAS-KIT); Co-supervisor: Prof. Lia Vasconselos (FCT-UNL)

Sept. 2009 - Dec. 2011: Master of Science, University of Applied Sciences Pinkafeld Austria „Energy and environmental management, Title of the thesis: "*Smart grid integration of electric vehicles as energy storage units for renewable based energy systems*". (Average grade level 1.8)

Nov. 2010- March 2011: Faculdade de Ciências da Universidade de Lisboa / Portugal, Exchange semester

Oct. 2005- Aug. 2009: Bachelor of Arts in Business, University of Applied sciences Kufstein / Austria, „European Energy economics", Title of thesis: "*National and international investments into ground-mounted multi-MW PV power plants through municipal utilities"*. (Average grade level 2.1)

July 2008- Feb. 2009: Universidad Católica de Córdoba in Argentina, Exchange semester (political sciences, system and organization theory, international business and logistics and others)

Scientific activities:

Jan. 2015: Cooperation with the Arizona State University – research & publication in the field of life cycle assessment

Sept. 2014: Co-organisation of a session within the 6th S.Net Conference in Karlruhe „Better Technologies With No Regret?", Life cycle Assessment, and interactive workshops

Since 2012: Reviewer for multiple conferences and journals (e.g. IEEE- EnergyCon, Journal of responsible Innovation etc.)

Aug. 2012: Participation at “1st Summer School on Renewable Energy Systems. Role and Use of Parliamentary Technology Assessment in Liège/Belgium”

Participation at the doctoral program at ITAS

Teaching and supervision activities (selection):

Internal supervision and co-supervision of several master and bachelor thesis at ITAS:

- Martin Hajek: „Analysis of potential Application areas of LIQHYSMES in the German energy grid“ - Technische Hochschule Ingolsadt
- Thom Versteeg: Master thesis “*Constructive Technology Assessment of emerging batter technology for grid-connected storage*” - VU (University Amsterdam)
- Jonas Graus: Bachelor thesis: „*Evaluation of electrochemical energy storage technologies for decentral applications*“ – Hochschule Furtwangen University

Co-supervision of multiple interdisciplinary projects / students from the applied university of Pforzheim (2012-2015) / highlight: 2013 cooperation with Illinois Institute of Technology on V2G system research

Lecture about “Decision making” within the ITAS doctoral program

Administrative activities:

Jan. 2015 –Dec 2015: PhD-spokesman for ITAS

Professional associations

Institute of Electrical and Electronics Engineers (IEEE) – Student member

IEEE Power & Energy society (PES)

Verband der Elektrotechnik (VDE) – Young professional member,

LIAISE-KIT – Knowledge for Decision Making / Expert

Grupo de Estudo sobre Avaliacao de Tecnologia (GrEAT)

Scientific grants & awards:

2010: Excellence scholarship of the FHS-Burgenland

Internships:

Apr.-Sept. 2009: Trianel GmbH Aachen / Project development

Working area: ground-mounted PV systems, offshore wind power project – Borkum West II, coal power plants Lünen and Krefeld in Germany

2000-2006: Others

Software skills:

MS Office, Visual Basic Application, PV Syst. PV-Sol, Matlab, EnergyPlan, SPSS, OpenLCA

Additional qualifications:

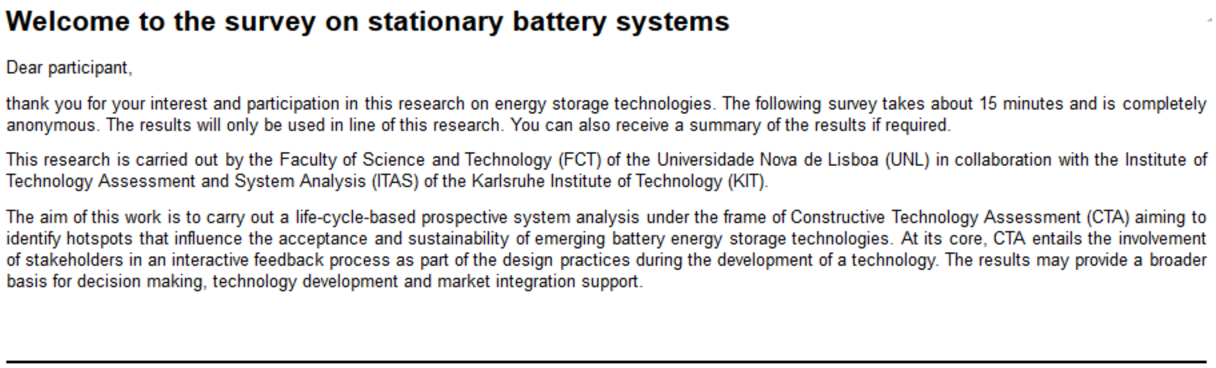
Investment analysis on renewable energy systems (Fh-Kufstein)

Languages:

German:	mother tongue
English:	fluent (C1)
Portuguese :	good (2 school years)
Spanish:	good (A2)
French:	basic (DELF B2)

Annex A

The following pages provide an overview of the conducted survey including all questions and the pairwise comparison within AHP.



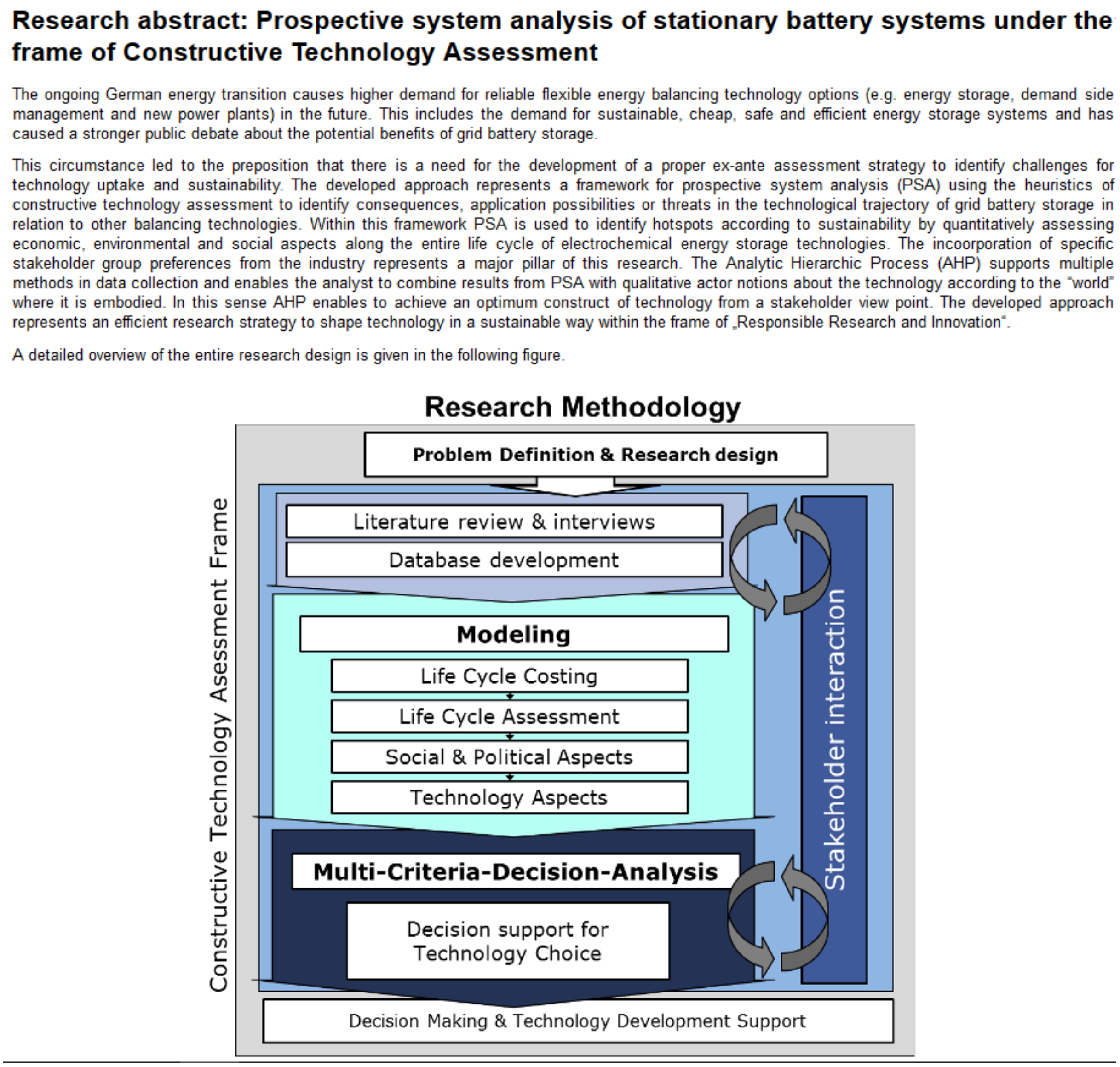
Welcome to the survey on stationary battery systems

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 required.

This research is carried out by the Faculty of Science and Technology (FCT) of the Universidade Nova de Lisboa (UNL) in collaboration with the Institute of Technology Assessment and System Analysis (ITAS) of the Karlsruhe Institute of Technology (KIT).

The aim of this work is to carry out a life-cycle-based prospective system analysis under the frame of Constructive Technology Assessment (CTA) aiming to identify hotspots that influence the acceptance and sustainability of emerging battery energy storage technologies. At its core, CTA entails the involvement of stakeholders in an interactive feedback process as part of the design practices during the development of a technology. The results may provide a broader basis for decision making, technology development and market integration support.

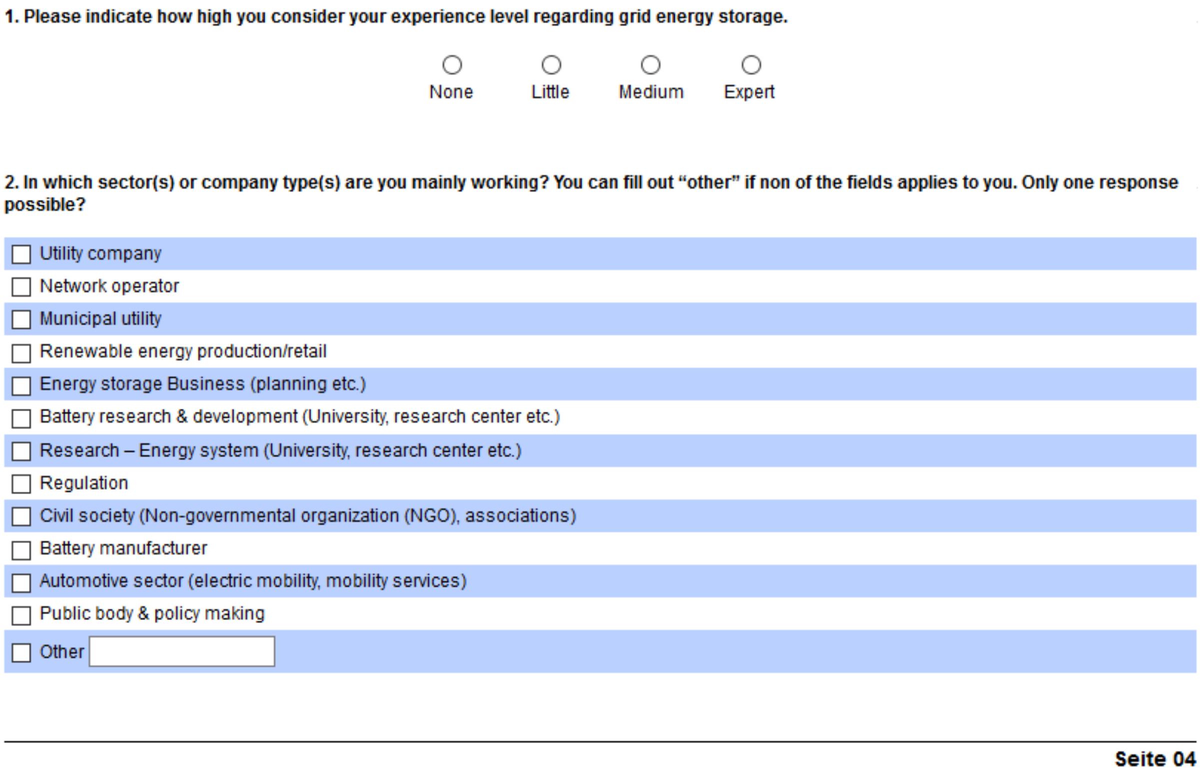


Research abstract: Prospective system analysis of stationary battery systems under the frame of Constructive Technology Assessment

The ongoing German energy transition causes higher demand for reliable flexible energy balancing technology options (e.g. energy storage, demand side management and new power plants) in the future. This includes the demand for sustainable, cheap, safe and efficient energy storage systems and has caused a stronger public debate about the potential benefits of grid battery storage.

This circumstance led to the preposition that there is a need for the development of a proper ex-ante assessment strategy to identify challenges for technology uptake and sustainability. The developed approach represents a framework for prospective system analysis (PSA) using the heuristics of constructive technology assessment to identify consequences, application possibilities or threats in the technological trajectory of grid battery storage in relation to other balancing technologies. Within this framework PSA is used to identify hotspots according to sustainability by quantitatively assessing economic, environmental and social aspects along the entire life cycle of electrochemical energy storage technologies. The incoorporation of specific stakeholder group preferences from the industry represents a major pillar of this research. The Analytic Hierarchic Process (AHP) supports multiple methods in data collection and enables the analyst to combine results from PSA with qualitative actor notions about the technology according to the "world" where it is embodied. In this sense AHP enables to achieve an optimum construct of technology from a stakeholder view point. The developed approach represents an efficient research strategy to shape technology in a sustainable way within the frame of „Responsible Research and Innovation".

A detailed overview of the entire research design is given in the following figure.



1. Please indicate how high you consider your experience level regarding grid energy storage.

○ None ○ Little ○ Medium ○ Expert

2. In which sector(s) or company type(s) are you mainly working? You can fill out "other" if non of the fields applies to you. Only one response possible?

☐ Utility company
☐ Network operator
☐ Municipal utility
☐ Renewable energy production/retail
☐ Energy storage Business (planning etc.)
☐ Battery research & development (University, research center etc.)
☐ Research – Energy system (University, research center etc.)
☐ Regulation
☐ Civil society (Non-governmental organization (NGO), associations)
☐ Battery manufacturer
☐ Automotive sector (electric mobility, mobility services)
☐ Public body & policy making
☐ Other

Seite 04

Energy System and Balancing technologies

The following questions are related to general issues regarding the energy system and balancing technologies.

3. Please indicate how much you agree with each statement regarding energy storage.

	Do not agree at all … Absolutely agree	No opinion
Sustainability aspects (environmental, economic and social factors) should play a bigger role in critical **investment & research decisions**.	○ ○ ○ ○ ○	○
Politics, industry and available studies underestimate the mid-term impacts of fluctuating renewables on the energy system architecture (e.g. markets, ownership relations and on system stability etc.).	○ ○ ○ ○ ○	○
The energy system after 2035 will be **strongly decentralized**.	○ ○ ○ ○ ○	○

4. Please rate the perceived relevance of different balancing technologies for a renewable energy source based electricity system.

	Low relevance … High relevance
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	☐

5. Please rate the level of political support to establish adequate market and legal regulations regarding the following techologies.

	Poor … Very Good	No Opinion
Centralized storage technologies (e.g. Pumped hydro storage, Compressed air energy storage etc.)	○ ○ ○ ○ ○	○
Flexible power plants (e.g. gas turbines, combined cycle gas turbine)	○ ○ ○ ○ ○	○
Stationary battery storage (e.g. Li-Ion-, Redox-Flow-, High-temperature-batteries)	○ ○ ○ ○ ○	○
Demand Side Management	○ ○ ○ ○ ○	○
Grid extension	○ ○ ○ ○ ○	○

6. Please rate in general the public acceptance of different storage and balancing technologies (regarding e.g. impact on landscape, perceived danger).

	Poor				Very good	No Opinion
Centralized storage technologies (Pumped hydro storage, compressed air energy storage, etc.)	○	○	○	○	○	○
Flexible power plants (gas turbines, combined cycle gas turbine)	○	○	○	○	○	○
Stationary battery storage (Li-Ion-, high-temperature-, Vanadium-Redox-Flow-battery etc.)	○	○	○	○	○	○
Demand side response	○	○	○	○	○	○
Grid extension	○	○	○	○	○	○

Seite 05

7. Please rate the contribution of different technologies regarding their socio-economic value (e.g. job creation, fair distribution of costs and benefits) on a regional level (major socio-economic regions – NUTS 1).

	Poor				Very good	No Opinion
Centralized balancing technologies (e.g. Pumped hydro storage, Compressed air energy storage etc.)	○	○	○	○	○	○
Flexible power plants (e.g. gas turbines)	○	○	○	○	○	○
Grid Battery Storage (Li-Ion, High Temperature, Redox-Flow etc.)	○	○	○	○	○	○
Demand Side Response	○	○	○	○	○	○
Grid Extension	○	○	○	○	○	○

Analytic Hierarchy Process (AHP)

Information: AHP Pairwise comparison

Dear participant,

in the following section we kindly ask you to please conduct **pairwise comparisons** based on **your preferences** as a part of a Analytical Hierarchic Process (AHP*). Your preferences will be used to calculate criteria weights for technology selection. AHP is a mathematical method used for decision making support and is based on the comparison of the criteria and sub-criteria.

11. 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".

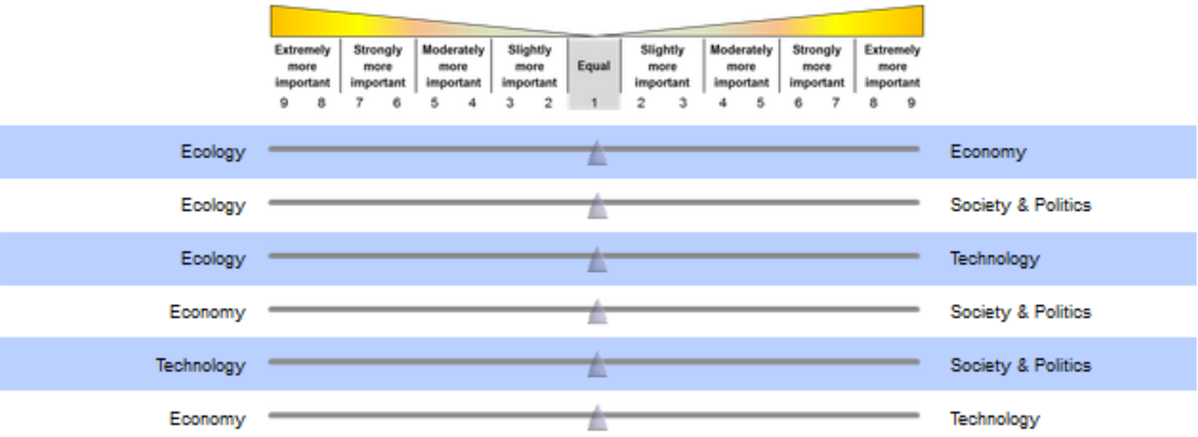
Sustainability criteria overview:

Ecology = Subcriteria: Damage to ecosystem diversity, damage to human health and ressource 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



Ecology	Economy
Ecology	Society & Politics
Ecology	Technology
Economy	Society & Politics
Technology	Society & Politics
Economy	Technology

Note

Please click on the cursor if your preference is "Equal" otherwise the survey will not proceed.

*Additional Information: The Analytic Hierarchy Process (AHP) was developed by Prof. Saaty (see Saaty 1980). It is a compensatory Multi-Criteria Decision Analysis method (MCDA) allowing numerical trade-offs among various dimensions. It allows to grasp physical - tangible factors related to an objective reality. By contrast it also enables to capture the psychological realm which is intangible as it is related to subjective ideas based on beliefs of the individual about himself or herself and the world of experience. For more information see: Thomas L. Saaty: Multicriteria decision making - the analytic hierarchy process. Planning, priority setting, resource allocation; 2. Auflage. RWS Publishing, Pittsburgh 1990, ISBN 0-9620317-2-0. Thomas L. Saaty: Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World. 3. Auflage. RWS Publishing, Pittsburgh 2001, ISBN 0-9620317-8-X

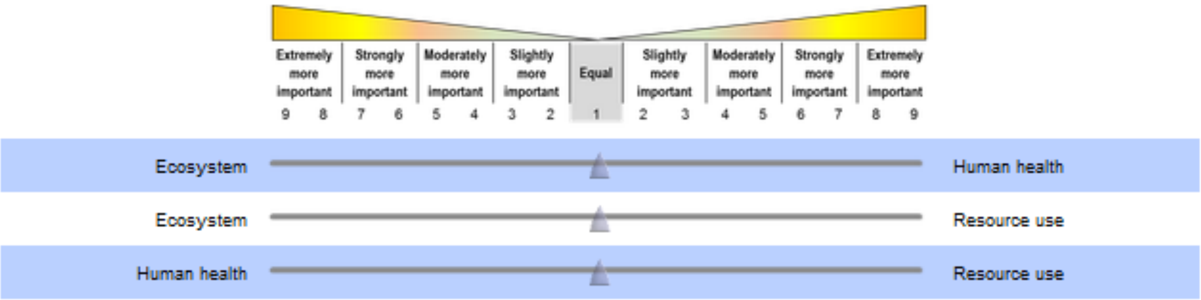
12. Please weight the importance of ecological impacts regarding storage and balancing technology choice.

Ecological criteria overview:

Damage to Ecosystem diversity = Diversity of species e.g. land use, fresh water eutrophication etc. based on database

Damage to Human health = Impact on human health e.g. climate change, ionizing radiation, particulate formation based on database.

Damage to Ressource availability = Use of minerals, water use, fossil fuel consumption based on database.



Note

Please click on the cursor if your preference is "Equal" otherwise the survey will not proceed.

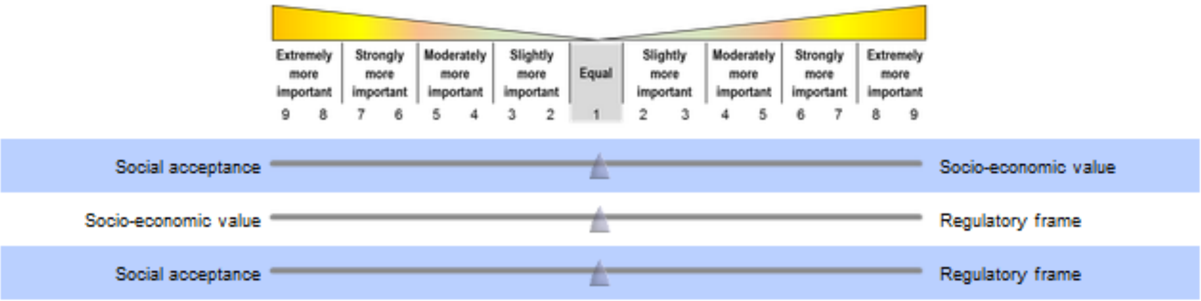
13. Please weight the importance of social factors regarding technology choice storage / balancing technology choice.

Social & policy criteria overview:

Social acceptance = e.g. effects on landscape, perceived danger based on expert judgement

Regulatory frame = e.g. availability of market rules, political support based on expert judgement

Socio-economic value = e.g. creation of jobs, contribution to local welfare based on expert judgement



Note

Please click on the cursor if your preference is "Equal" otherwise the survey will not proceed.

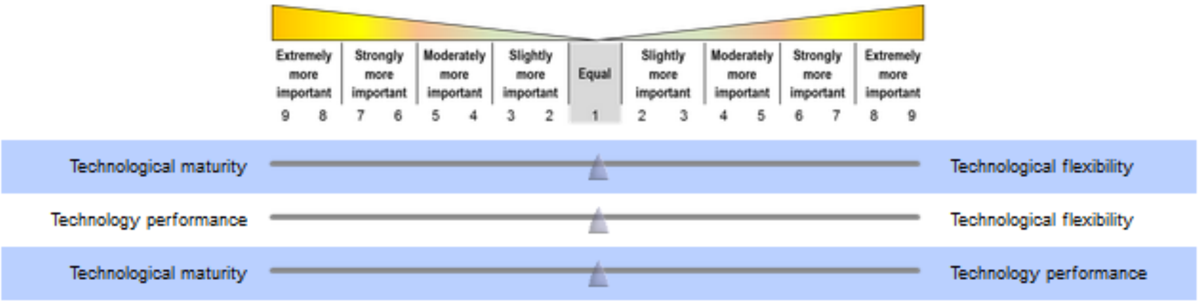
14. Please weight the relative importance of <u>technical aspects</u> regarding storage technology / balancing technology choice.

Technological criteria overview:

<u>Technological maturity</u> = Ease of use, track record represented by total global installations, no. of patents and citations in scientific literature

<u>Technology performance</u> = Service time (e.g. cycles and years), energy & power density and charge/discharge efficiency based on technology database

<u>Technological flexibility</u> = Response time (kW/min), No. of application possibilities based on technology database



Technological maturity	Technological flexibility
Technology performance	Technological flexibility
Technological maturity	Technology performance

Note

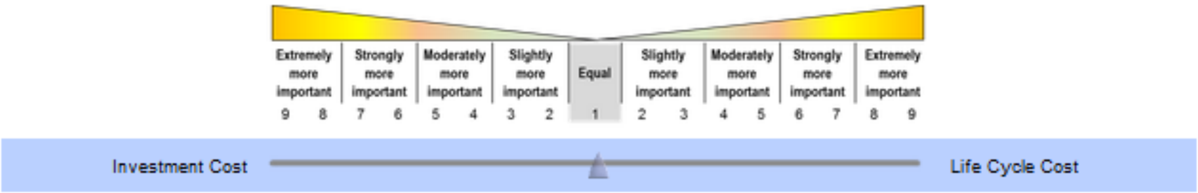
Please click on the cursor if your preference is "Equal" otherwise the survey will not proceed.

15. Please weight the relative importance of <u>economic performance</u> regarding storage technology / balancing technology choice

Criteria overview:

<u>Investment cost</u> = Initial investment until operable status based on technology database

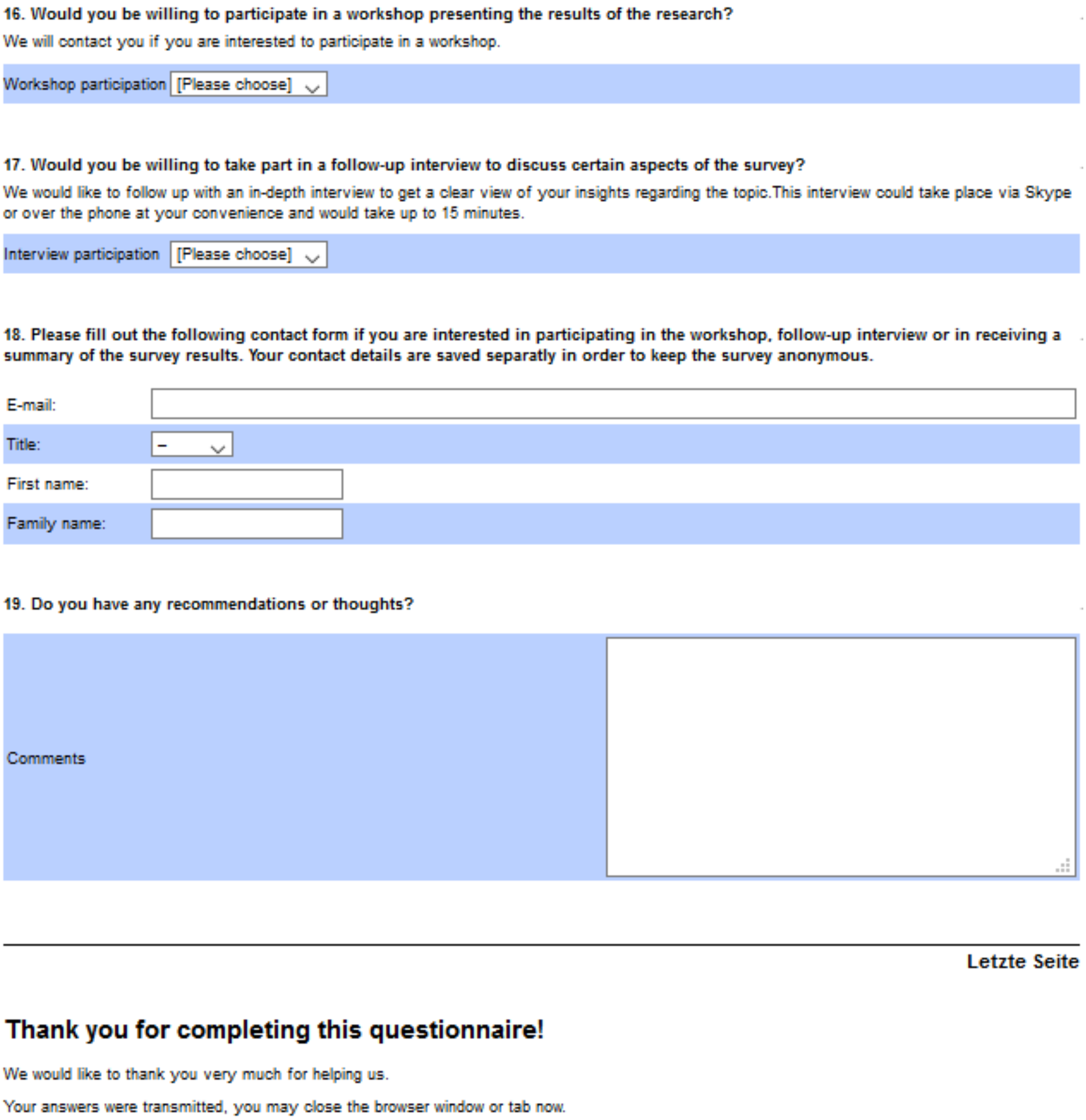
<u>Life Cycle Cost</u> = Stands for the "total" costs generated by a system including initial investment, capital, replacement, operation, energy and disposal costs etc. based on technology database.



Investment Cost	Life Cycle Cost

Note

Please click on the cursor if your preference is "Equal" otherwise the survey will not proceed.



16. Would you be willing to participate in a workshop presenting the results of the research?

We will contact you if you are interested to participate in a workshop.

Workshop participation [Please choose]

17. Would you be willing to take part in a follow-up interview to discuss certain aspects of the survey?

We would like to follow up with an in-depth interview to get a clear view of your insights regarding the topic.This interview could take place via Skype or over the phone at your convenience and would take up to 15 minutes.

Interview participation [Please choose]

18. Please fill out the following contact form if you are interested in participating in the workshop, follow-up interview or in receiving a summary of the survey results. Your contact details are saved separately in order to keep the survey anonymous.

E-mail:
Title: –
First name:
Family name:

19. Do you have any recommendations or thoughts?

Comments

Letzte Seite

Thank you for completing this questionnaire!

We would like to thank you very much for helping us.

Your answers were transmitted, you may close the browser window or tab now.

Annex B

The applied patent research methodology is highly dependent on the study goal, available time and money as well as topic [289]. It is possible to generally divide quantitative and qualitative patent research. The first includes the evaluation of patents by reading single patents and to e.g. determine their value which is not considered as recommendable due to the vast amount of available patent documents. Quantitative methods are carried out by the use of bibliometric approaches and indicators. The first represents merely the statistical analysis of bibliometric data, and the latter a measure to derive information about specific situations and developments regarding patents [290], [291]. In this case the latter is used as these approaches allow it to unveil e.g. certain technology development trends, to identify market leaders or to search for key markets for specific technology solutions. Such statistical analyses can be based on the available number of patents related to a certain IPC-class, one inventor or a certain time period [290]. It does however not substitute in-depth patent analysis as it is not possible to accurately evaluate real importance of a patent only by the use of quantitative approaches.

There are worldwide over 100 patent data sources available each with a different data range and suitable for different purposes. Most of these sources are freely available and provide access to patents and bibliographic data [290]. The most popular ones will be briefly introduced here. The World intellectual property organization (WIPO) provides a global data base named Patentscope [292], Esp@cenet is a database provided by the European patent office [293] and the German patent office DPMA provides Depatisnet [196]. All three provide patent collections from a multitude of countries.

However, there are differences between the sources regarding: data coverage, search functionality, result list of records, bibliographic view and patent data export. The search modes in the three databases are similarly based on command line searching and search fields. Searches can be conducted either by the use of keywords or technological classifications or the combination of both to identify patents of certain patents [294]. Patentscope owns a high magnitude of patent collections with full text searching capability, whereas the other are very limited. A good in-depth comparison of differences between Patenscope, Espacenet and Depatisnet is given in [295]. A brief overview of different patent data sources is given in table 1.

Tab. 1: Brief overview of Patentscope, Espacenet and Depatis based on [295]

Name	**Patent records**	**Available patent collections (countries)**	**Patent collections with full text search capability**	**Source**
Germany patent office - Depatisnet	~90 Mil.	101	1	[196]
European patent office - Espacenet	~ 90 Mil.	101	2	[293]
World intellectual property organization (WIPO) Patentscope	~37 mil.	39	19	[292]
Overview for more databases	-	-		[296]

A pure keyword based search inhibits the risk of potentially excluding patents through a too narrow combination of keywords related to a certain area. Or vice versa to include wrong patents by a too loose formulation. Another associated problem to this kind of research are differences in the wording used in patent applications within different jurisdictions [290]. Changing a keyword or logical operator may lead to completely different results. However, a purely IPC based search allows only a certain resolution regarding technology classification (e.g. batteries to H01M*[32]). It is worth to mention that patents are categorized within the international patent classification (IPC) into different units. Each patent is classified in up to 70.000 subcategories. Categorization is normally organized by choosing a main group, a subclass, a group and finally a subgroup. There are in total eight section defined based on [292], [297].

The combination of both can circumvent these challenges. The recently introduced cooperative patent classifications (CPC) between the United States Patent and Trademark Office (USPTO) and EPO allows even a more refined search manner of technologies in a certain area e.g. related to transmission or distribution, transport etc. [298], [294]. The search combination in frame of this work consists the IPC main classes, country codes for priority countries and keywords for technology.Table 2 provides an overview of used classifications in frame of this work and the mentioned CPC groups.

Tab. 2: Considered technologies and their corresponding keywords, CPC and IPC [294], [298] and [292]

Technology keyword	**CPC subclass and IPC main class** **Groups & subgroups**	
Lithium	H01M Y02E Y02T	10/052 60/122 10/7011
High-temperature batteries (NaS, NaNiCl)	H01M	10/39
Regenerative fuel cells (redox-flow batteries)	H01M Y02E	8/188 60/528
Lead Acid, PbA, VRLA, AGM	H01M Y02E Y02T	2/28, 4/14-4/23, 4/73-4/84, 10/12?*, 10/06-10/18, 10/342 60/126 10/7016

Depatisnet is used for this research as it allows to gather in-depth information about patents by a unique feature – it´s IKOFAX search mode. IKOFAX is a command line search interface where searches can be constructed by an internal search language. It allows to conduct complex search queries e.g. by combination of IPC and CPC entries as well as relevant keywords within a certain period related to a priority country. An example for redox flow battery patents from Japan max be as follows: “*01.01.1997<=/PUB<=01.01.2018 AND (H01M8/18?)/ICB AND (Vanadium)/BI AND (JP/PRC)*”. The ability to conduct complex search requests by logic combination outbalances the relatively low abilities of full text search in Depatisnet. The evaluation of the gathered data is carried out by the use of Excel. It is recommended to use professional text mining software for future research as Excel only provides restricted possibilities to conduct bibliometric analyses.

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[32] H01M – “*PROCESSES OR MEANS, e.g. BATTERIES, FOR THE DIRECT CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY*” [292]

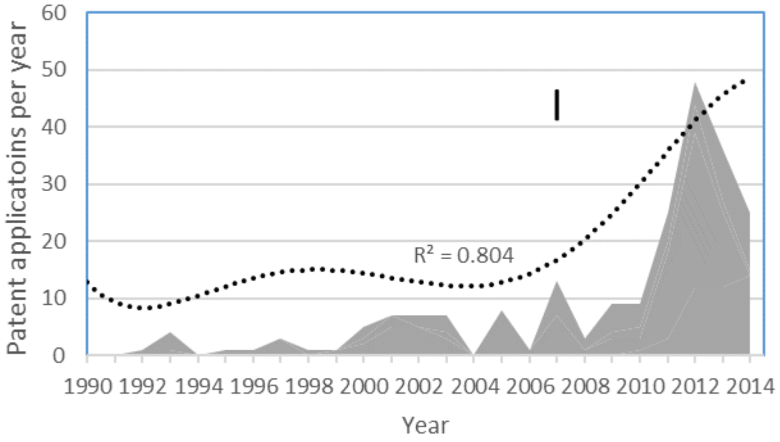


Fig. 1: Innovation life cycle stage of used to determine the maturity of VRFB

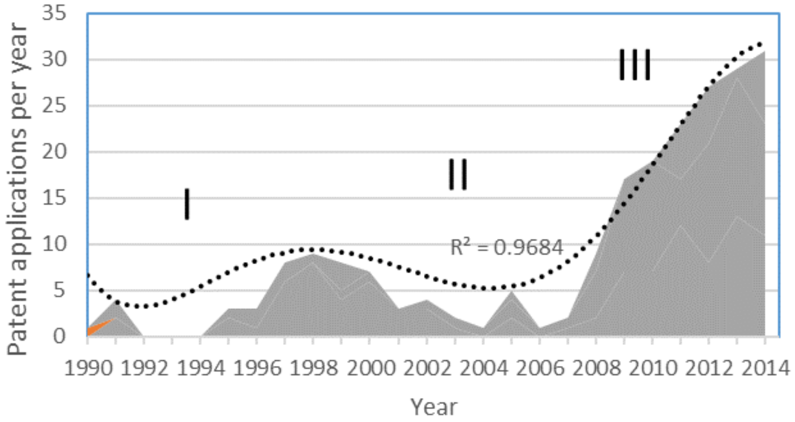


Fig. 2: Innovation life cycle stage of used to determine the maturity of high temperature batteries (NaS and NaNiCl)

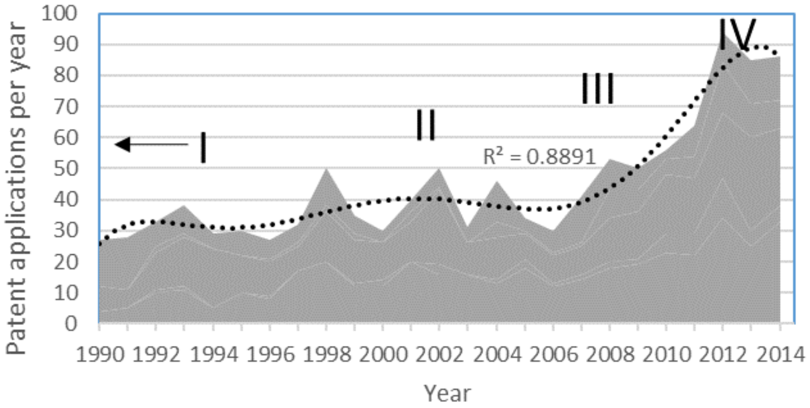


Fig. 3: Innovation life cycle stage of used to determine the maturity of VRLA

Tab. 3: Results of the literature review regarding the maturity degree of different energy storage technologies

	CSIRO 2016				Fereira et al 2015		Luo et al 201	Sterner et al 2014	Delooitte 20	EASE 2017
	TRL	MRL	Market trends		Maturity levels 1 to 5		Maturity lev	TRL	Maturity level	
LFP	9	9	strong growth	Robust chem. Market leader, increasing no.	4		3	7.8	4.6	5
VRFB	8	7	Env. Concerns, short life in demo		3		2.5	6.3	4.6	4
NaNiCl	8	7	Anticipate growth	GE & FIAMM	4		4	7.8	4.7	5
NaS	6	6	N/A	Niche Applications	4		4	7.8	4.7	5
CAES	9	7	stable	round trip efficiency	5		4	6.8	4.8	
PHS	9	10	decline	Limited areas	5		5	9	5	
VRLA	9	10	marg. Growth	Benchmark technology	5		5	9	4.6	6
NCA	9	9	strong growth	Tesla el. Veh	4		3	7.8	4.6	5
NMC	9	9	strong growth	redidential and commercial storage, e.g. Tesla powerwall	4		3	7.8	4.6	5
LTO	N/A	N/A	N/A	N/A	4		3	7.8	4.6	5
Advanced P	8	7	Anticipate growth	significant pot. Based on ex. Techn.	5		N/A	N/A		
NiCd	9	9	decline	Decline due to env. Probl. & memory effect	4		N/A	N/A		
Zinc bromid	9	8	Growth	N/A	2		N/A	N/A		
Flywheel	7	8	Stable	Off-grid appl. Deployment	4		N/A	N/A		
Super/Doubl	7	8	stable	Niche Applications	3		N/A	N/A		
SMES	7	5	N/A	Complex technology	3		N/A	N/A		

Annex C

The following figure provide an overview about calculated learning curves and scale effects of the power conversion system. Details can be obtained from the literature provided in the main text.

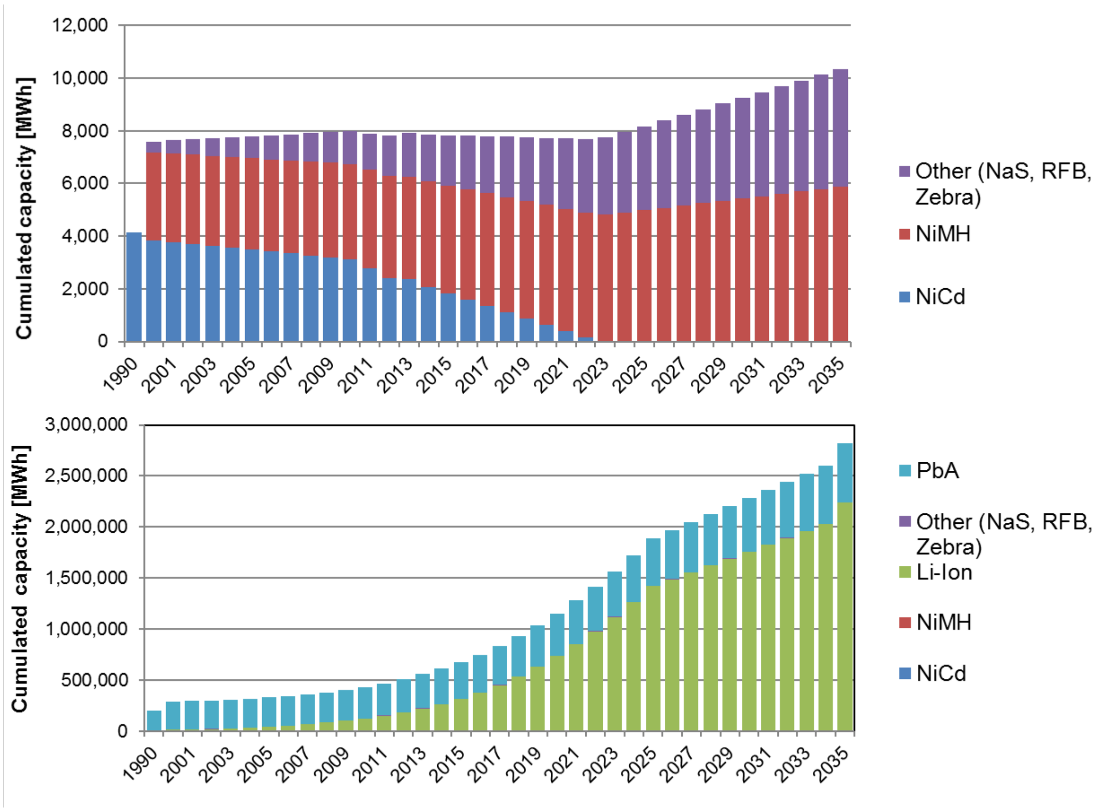


Fig. 4: Cumulated battery production rate for learning curve calculus

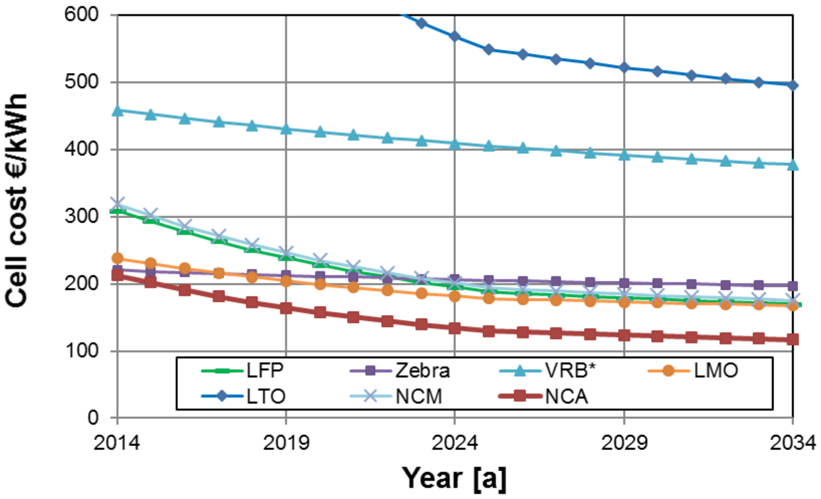


Fig. 5: Excerpt of base case for used learning curves for LCC

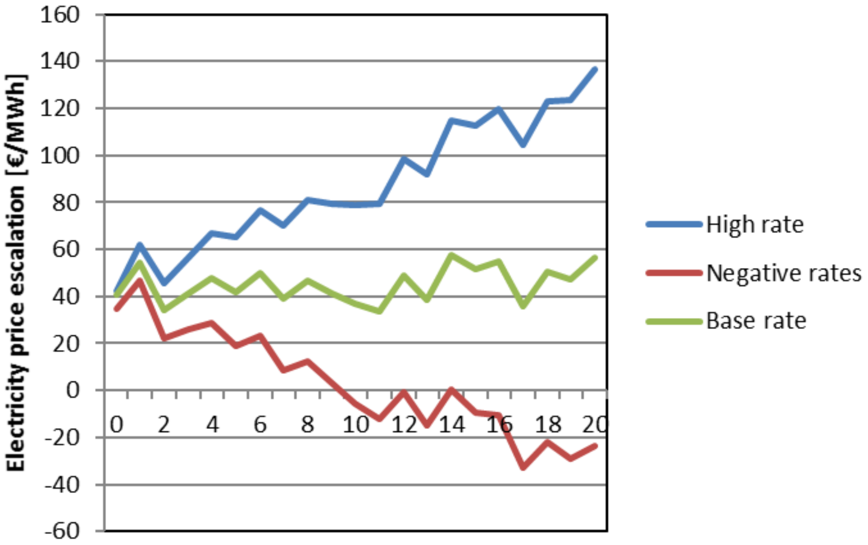


Fig. 6: Electricity price spread calculus used for LCC-MCS

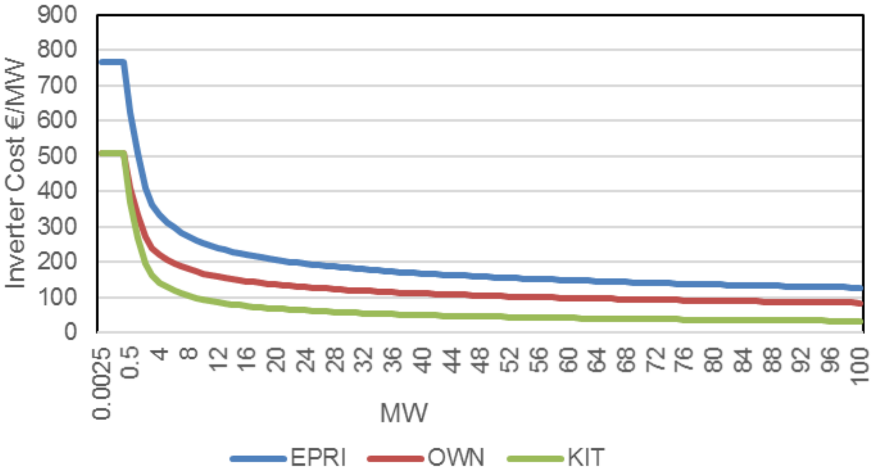
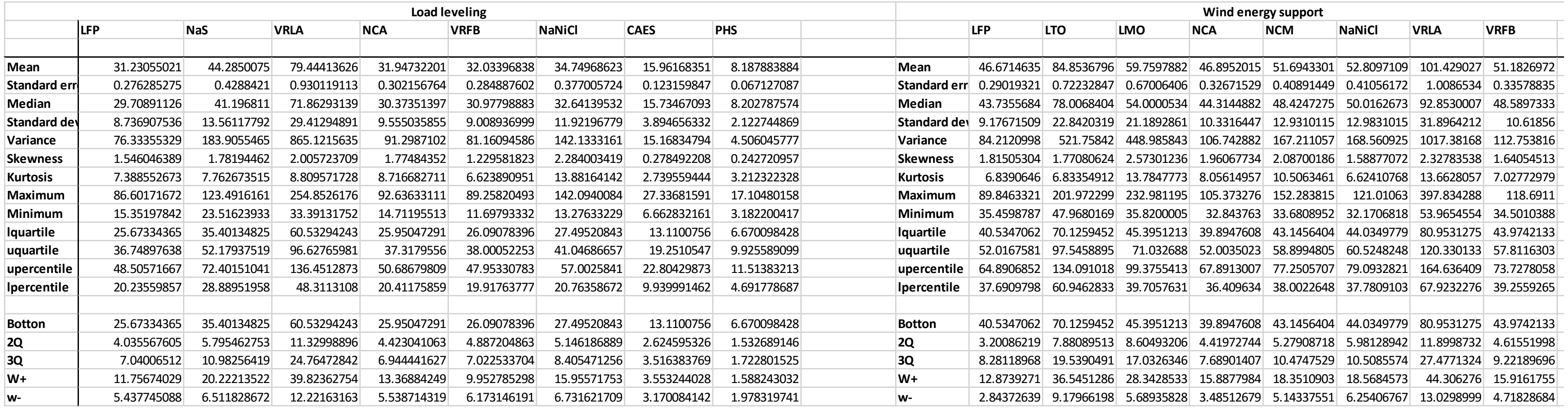


Fig. 7: Scale effects of Inverter size – the average (own) is used for calculus

Annex D

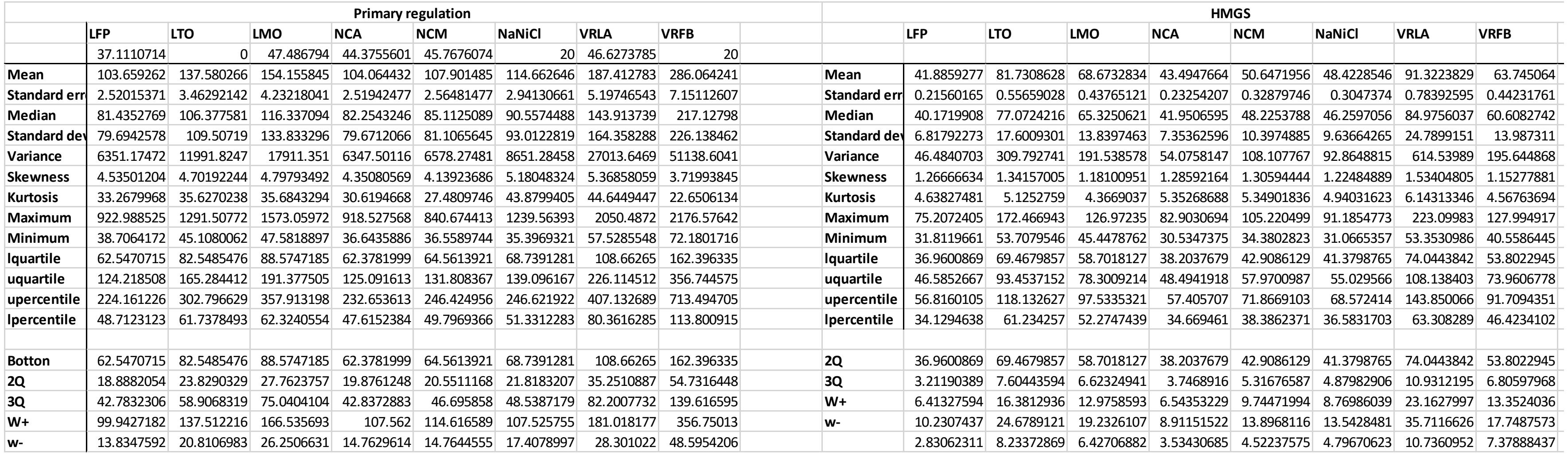
Tab. 4: Numeric LCC-MCS results for ETS (Energy time shift / Load levelling) and WES (Wind energy support)



	Load leveling							
	LFP	NaS	VRLA	NCA	VRFB	NaNiCl	CAES	PHS
Mean	31.23055021	44.2850075	79.44413626	31.94732201	32.03396838	34.74968623	15.96168351	8.187883884
Standard err	0.276285275	0.4288421	0.930119113	0.302156764	0.284887602	0.377005724	0.123159847	0.067127087
Median	29.70891126	41.196811	71.86293139	30.37351397	30.97798883	32.64139532	15.73467093	8.202787574
Standard dev	8.736907536	13.56117792	29.41294891	9.555035855	9.008936999	11.92196779	3.894656332	2.122744869
Variance	76.33355329	183.9055465	865.1215635	91.2987102	81.16094586	142.1333161	15.16834794	4.506045777
Skewness	1.546046389	1.78194462	2.005723709	1.77484352	1.229581823	2.284003419	0.278492208	0.242720957
Kurtosis	7.388552673	7.762673515	8.809571728	8.716682711	6.623890951	13.88164142	2.739559444	3.212322328
Maximum	86.60171672	123.4916161	254.8526176	92.63633111	89.25820493	142.0940084	27.33681591	17.10480158
Minimum	15.35197842	23.51623933	33.39131752	14.71195513	11.69793332	13.27633229	6.662832161	3.182200417
lquartile	25.67334365	35.40134825	60.53294243	25.95047291	26.09078396	27.49520843	13.1100756	6.670098428
uquartile	36.74897638	52.17937519	96.62765981	37.3179556	38.00052253	41.04686657	19.2510547	9.925589099
upercentile	48.50571667	72.40151041	136.4512873	50.68679809	47.95330783	57.0025841	22.80429873	11.51383213
lpercentile	20.23559857	28.88951958	48.3113108	20.41175859	19.91763777	20.76358672	9.939991462	4.691778687
Botton	25.67334365	35.40134825	60.53294243	25.95047291	26.09078396	27.49520843	13.1100756	6.670098428
2Q	4.035567605	5.795462753	11.32998896	4.423041063	4.887204863	5.146186889	2.624595326	1.532689146
3Q	7.04006512	10.98256419	24.76472842	6.944441627	7.022533704	8.405471256	3.516383769	1.722801525
W+	11.75674029	20.22213522	39.82362754	13.36884249	9.952785298	15.95571753	3.553244028	1.588243032
w-	5.437745088	6.511828672	12.22163163	5.538714319	6.173146191	6.731621709	3.170084142	1.978319741

	Wind energy support							
	LFP	LTO	LMO	NCA	NCM	NaNiCl	VRLA	VRFB
Mean	46.6714635	84.8536796	59.7597882	46.8952015	51.6943301	52.8097109	101.429027	51.1826972
Standard err	0.29019321	0.72232847	0.67006406	0.32671529	0.40891449	0.41056172	1.0086534	0.33578835
Median	43.7355684	78.0068404	54.0000534	44.3144882	48.4247275	50.0162673	92.8530007	48.5897333
Standard dev	9.17671509	22.8420319	21.1892861	10.3316447	12.9310115	12.9831015	31.8964212	10.61856
Variance	84.2120998	521.75842	448.985843	106.742882	167.211057	168.560925	1017.38168	112.753816
Skewness	1.81505304	1.77080624	2.57301236	1.96067734	2.08700186	1.58877072	2.32783538	1.64054513
Kurtosis	6.8390646	6.83354912	13.7847773	8.05614957	10.5063461	6.62410768	13.6628057	7.02772979
Maximum	89.8463321	201.972299	232.981195	105.373276	152.283815	121.01063	397.834288	118.6911
Minimum	35.4598787	47.9680169	35.8200005	32.843763	33.6808952	32.1706818	53.9654554	34.5010388
lquartile	40.5347062	70.1259452	45.3951213	39.8947608	43.1456404	44.0349779	80.9531275	43.9742133
uquartile	52.0167581	97.5458895	71.032688	52.0035023	58.8994805	60.5248248	120.330133	57.8116303
upercentile	64.8906852	134.091018	99.3755413	67.8913007	77.2505707	79.0932821	164.636409	73.7278058
lpercentile	37.6909798	60.9462833	39.7057631	36.409634	38.0022648	37.7809103	67.9232276	39.2559265
Botton	40.5347062	70.1259452	45.3951213	39.8947608	43.1456404	44.0349779	80.9531275	43.9742133
2Q	3.20086219	7.88089513	8.60493206	4.41972744	5.27908718	5.98128942	11.8998732	4.61551998
3Q	8.28118968	19.5390491	17.0326346	7.68901407	10.4747529	10.5085574	27.4771324	9.22189696
W+	12.8739271	36.5451286	28.3428533	15.8877984	18.3510903	18.5684573	44.306276	15.9161755
w-	2.84372639	9.17966198	5.68935828	3.48512679	5.14337551	6.25406767	13.0298999	4.71828684

Tab. 5: Numeric LCC-MCS results for PR (Primary regulation) and HMGS (hybrid micro grid system)



	Primary regulation							
	LFP	LTO	LMO	NCA	NCM	NaNiCl	VRLA	VRFB
	37.1110714	0	47.486794	44.3755601	45.7676074	20	46.6273785	20
Mean	103.659262	137.580266	154.155845	104.064432	107.901485	114.662646	187.412783	286.064241
Standard err	2.52015371	3.46292142	4.23218041	2.51942477	2.56481477	2.94130661	5.19746543	7.15112607
Median	81.4352769	106.377581	116.337094	82.2543246	85.1125089	90.5574488	143.913739	217.12798
Standard dev	79.6942578	109.50719	133.833296	79.6712066	81.1065645	93.0122819	164.358288	226.138462
Variance	6351.17472	11991.8247	17911.351	6347.50116	6578.27481	8651.28458	27013.6469	51138.6041
Skewness	4.53501204	4.70192244	4.79793492	4.35080569	4.13923686	5.18048324	5.36858059	3.71993845
Kurtosis	33.2679968	35.6270238	35.6843294	30.6194668	27.4809746	43.8799405	44.6449447	22.6506134
Maximum	922.988525	1291.50772	1573.05972	918.527568	840.674413	1239.56393	2050.4872	2176.57642
Minimum	38.7064172	45.1080062	47.5818897	36.6435886	36.5589744	35.3969321	57.5285548	72.1801716
lquartile	62.5470715	82.5485476	88.5747185	62.3781999	64.5613921	68.7391281	108.66265	162.396335
uquartile	124.218508	165.284412	191.377505	125.091613	131.808367	139.096167	226.114512	356.744575
upercentile	224.161226	302.796629	357.913198	232.653613	246.424956	246.621922	407.132689	713.494705
lpercentile	48.7123123	61.7378493	62.3240554	47.6152384	49.7969366	51.3312283	80.3616285	113.800915
Botton	62.5470715	82.5485476	88.5747185	62.3781999	64.5613921	68.7391281	108.66265	162.396335
2Q	18.8882054	23.8290329	27.7623757	19.8761248	20.5511168	21.8183207	35.2510887	54.7316448
3Q	42.7832306	58.9068319	75.0404104	42.8372883	46.695858	48.5387179	82.2007732	139.616595
W+	99.9427182	137.512216	166.535693	107.562	114.616589	107.525755	181.018177	356.75013
w-	13.8347592	20.8106983	26.2506631	14.7629614	14.7644555	17.4078997	28.301022	48.5954206

	HMGS							
	LFP	LTO	LMO	NCA	NCM	NaNiCl	VRLA	VRFB
Mean	41.8859277	81.7308628	68.6732834	43.4947664	50.6471956	48.4228546	91.3223829	63.745064
Standard err	0.21560165	0.55659028	0.43765121	0.23254207	0.32879746	0.3047374	0.78392595	0.44231761
Median	40.1719908	77.0724216	65.3250621	41.9506595	48.2253788	46.2597056	84.9756037	60.6082742
Standard dev	6.81792273	17.6009301	13.8397463	7.35362596	10.3974885	9.63664265	24.7899151	13.987311
Variance	46.4840703	309.792741	191.538578	54.0758147	108.107767	92.8648815	614.53989	195.644868
Skewness	1.26666634	1.34157005	1.18100951	1.28592164	1.30594444	1.22484889	1.53404805	1.15277881
Kurtosis	4.63827481	5.1252759	4.3669037	5.35268688	5.34901836	4.94031623	6.14313346	4.56763694
Maximum	75.2072405	172.466943	126.97235	82.9030694	105.220499	91.1854773	223.09983	127.994917
Minimum	31.8119661	53.7079546	45.4478762	30.5347375	34.3802823	31.0665357	53.3530986	40.5586445
lquartile	36.9600869	69.4679857	58.7018127	38.2037679	42.9086129	41.3798765	74.0443842	53.8022945
uquartile	46.5852667	93.4537152	78.3009214	48.4941918	57.9700987	55.029566	108.138403	73.9606778
upercentile	56.8160105	118.132627	97.5335321	57.405707	71.8669103	68.572414	143.850066	91.7094351
lpercentile	34.1294638	61.234257	52.2747439	34.669461	38.3862371	36.5831703	63.308289	46.4234102
2Q	36.9600869	69.4679857	58.7018127	38.2037679	42.9086129	41.3798765	74.0443842	53.8022945
3Q	3.21190389	7.60443594	6.62324941	3.7468916	5.31676587	4.87982906	10.9312195	6.80597968
W+	6.41327594	16.3812936	12.9758593	6.54353229	9.74471994	8.76986039	23.1627997	13.3524036
w-	10.2307437	24.6789121	19.2326107	8.91151522	13.8968116	13.5428481	35.7116626	17.7487573
	2.83062311	8.23372869	6.42706882	3.53430685	4.52237575	4.79670623	10.7360952	7.37888437

Annex E

Tab. 6: Numeric LCA-MCS results for ETS (Energy time shift) and the three recipe endpoints

	ETS																							
	LFP	**NaS**	**CAES**	**NCA**	**PHS**	**NaNiCl**	**VRLA**	**VRFB**	**LFP**	**NaS**	**CAES**	**NCA**	**PHS**	**NaNiCl**	**VRLA**	**VRFB**	**LFP**	**NaS**	**CAES**	**NCA**	**PHS**	**NaNiCl**	**VRLA**	**VRFB**
	DRA	**DRA**	**DRA**	**DRA**	**DRA**	**DRA**	**DRA**	**DRA**	**DE**	**DE**	**DE**	**DE**	**DE**	**DE**	**DE**	**DE**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**
	0.0189	0.0261	0.0616	0.0221	0.0217	0.0285	0.0423	0.0266	0.0121	0.0152	0.0293	0.0137	0.0266	0.0233	0.0273	0.0242	0.0245	0.0311	0.0548	0.0274	0.0264	0.0291	0.0346	0.0300
Mean	0.0228	0.0286	0.0608	0.0237	0.0215	0.0288	0.0548	0.0303	0.0135	0.0162	0.0278	0.0141	0.0174	0.0156	0.0192	0.0176	0.0281	0.0334	0.0525	0.0286	0.0329	0.0353	0.0477	0.0426
Standard error	0.0005	0.0008	0.0013	0.0005	0.0003	0.0009	0.0037	0.0007	0.0002	0.0003	0.0006	0.0002	0.0002	0.0002	0.0005	0.0003	0.0005	0.0006	0.0011	0.0004	0.0003	0.0010	0.0021	0.0013
Median	0.0213	0.0274	0.0591	0.0230	0.0213	0.0269	0.0496	0.0299	0.0133	0.0157	0.0268	0.0139	0.0171	0.0152	0.0188	0.0173	0.0272	0.0323	0.0509	0.0281	0.0329	0.0332	0.0448	0.0411
Standard deviation	0.0024	0.0034	0.0058	0.0022	0.0012	0.0040	0.0164	0.0030	0.0008	0.0012	0.0026	0.0007	0.0011	0.0010	0.0023	0.0011	0.0023	0.0029	0.0048	0.0018	0.0016	0.0044	0.0092	0.0056
Variance	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
Skewness	1.1995	1.3192	0.2352	2.0577	0.3737	1.3490	1.6428	0.9069	0.7816	1.1707	0.1899	2.0133	0.5176	1.3570	0.9763	0.4194	1.0028	1.2542	0.2350	2.0428	0.1051	1.3508	1.5028	1.0560
Kurtosis	3.5522	3.8527	1.6989	7.6036	2.6644	4.0605	5.7417	2.8380	2.5478	3.8513	1.6881	7.4856	2.8445	4.3210	3.7151	2.1533	2.9512	3.9076	1.6319	7.5916	2.3092	4.0911	5.2540	3.1149
Maximum	0.0293	0.0370	0.0715	0.0314	0.0244	0.0400	0.1068	0.0373	0.0153	0.0193	0.0325	0.0167	0.0201	0.0186	0.0253	0.0197	0.0334	0.0408	0.0615	0.0350	0.0362	0.0476	0.0760	0.0563
Minimum	0.0202	0.0246	0.0526	0.0213	0.0195	0.0248	0.0376	0.0271	0.0124	0.0145	0.0238	0.0133	0.0157	0.0145	0.0163	0.0157	0.0253	0.0296	0.0461	0.0266	0.0302	0.0310	0.0371	0.0367
lquartile	0.0210	0.0262	0.0546	0.0225	0.0205	0.0254	0.0426	0.0275	0.0127	0.0153	0.0252	0.0137	0.0166	0.0146	0.0173	0.0166	0.0263	0.0313	0.0476	0.0276	0.0313	0.0315	0.0411	0.0380
uquartile	0.0243	0.0299	0.0662	0.0248	0.0225	0.0311	0.0615	0.0317	0.0139	0.0167	0.0303	0.0144	0.0183	0.0163	0.0200	0.0187	0.0294	0.0346	0.0570	0.0295	0.0339	0.0379	0.0512	0.0448
upercentile	0.0268	0.0364	0.0696	0.0264	0.0231	0.0362	0.0815	0.0360	0.0149	0.0187	0.0312	0.0150	0.0187	0.0173	0.0233	0.0195	0.0326	0.0397	0.0590	0.0308	0.0351	0.0433	0.0636	0.0532
lpercentile	0.0202	0.0246	0.0526	0.0213	0.0195	0.0248	0.0376	0.0271	0.0124	0.0145	0.0238	0.0133	0.0157	0.0145	0.0163	0.0157	0.0253	0.0296	0.0461	0.0266	0.0302	0.0310	0.0371	0.0367
Botton	0.0210	0.0262	0.0546	0.0225	0.0205	0.0254	0.0426	0.0275	0.0127	0.0153	0.0252	0.0137	0.0166	0.0146	0.0173	0.0166	0.0263	0.0313	0.0476	0.0276	0.0313	0.0315	0.0411	0.0380
2Q	0.0003	0.0012	0.0045	0.0005	0.0008	0.0016	0.0070	0.0025	0.0006	0.0003	0.0016	0.0002	0.0005	0.0006	0.0015	0.0007	0.0009	0.0010	0.0033	0.0005	0.0017	0.0017	0.0037	0.0031
3Q	0.0030	0.0025	0.0071	0.0018	0.0012	0.0042	0.0119	0.0017	0.0006	0.0011	0.0035	0.0005	0.0012	0.0011	0.0012	0.0014	0.0022	0.0023	0.0061	0.0014	0.0010	0.0047	0.0063	0.0037
W+	0.0025	0.0066	0.0034	0.0016	0.0006	0.0051	0.0200	0.0043	0.0010	0.0020	0.0009	0.0006	0.0004	0.0010	0.0033	0.0008	0.0032	0.0052	0.0021	0.0013	0.0011	0.0054	0.0124	0.0084
w-	0.0008	0.0017	0.0020	0.0012	0.0010	0.0006	0.0050	0.0004	0.0004	0.0008	0.0014	0.0004	0.0009	0.0001	0.0010	0.0009	0.0010	0.0018	0.0015	0.0010	0.0011	0.0006	0.0040	0.0013

Tab. 7: Numeric LCA-MCS results for ETS (Energy time shift) and the three recipe endpoints

	PR																							
	LFP	NaS	LTO	NCA	NCM	NaNiCl	VRLA	RFB	LFP	NaS	LTO	NCA	NCM	NaNiCl	VRLA	RFB	LFP	NaS	LTO	NCA	NCM	NaNiCl	VRLA	RFB
	DRA	DRA	DRA	DRA	DRA	DRA	DRA	DRA	DE	DE	DE	DE	DE	DE	DE	DE	DHH	DHH	DHH	DHH	DHH	DHH	DHH	DHH
Mean	0.025263	0.08903	0.021043	0.025992	0.032042	0.035086	0.072031	0.032629	0.014939	0.036712	0.011982	0.015606	0.016364	0.017918	0.022114	0.018717	0.03097	0.084082	0.032728	0.031035	0.04379	0.04261	0.051076	0.041293
Standard error	0.000822	0.00693	0.000549	0.000675	0.001355	0.001671	0.007133	0.00105	0.000384	0.002352	0.00017	0.000307	0.000419	0.000511	0.001038	0.000423	0.000914	0.005812	0.00082	0.00062	0.001581	0.001864	0.004052	0.002025
Median	0.024449	0.081442	0.02049	0.025257	0.029982	0.034084	0.05832	0.030803	0.014571	0.033894	0.011866	0.015414	0.016031	0.017719	0.020266	0.018287	0.029937	0.077366	0.031886	0.030508	0.041124	0.041554	0.042473	0.036818
Standard deviation	0.003677	0.030993	0.002456	0.00302	0.006059	0.007475	0.031899	0.004694	0.001719	0.010517	0.000758	0.001373	0.001876	0.002285	0.00464	0.001891	0.004086	0.025991	0.003665	0.002771	0.007071	0.008336	0.018122	0.009055
Variance	1.35E-05	0.000961	6.03E-06	9.12E-06	3.67E-05	5.59E-05	0.001018	2.2E-05	2.95E-06	0.000111	5.75E-07	1.88E-06	3.52E-06	5.22E-06	2.15E-05	3.58E-06	1.67E-05	0.000676	1.34E-05	7.68E-06	5E-05	6.95E-05	0.000328	8.2E-05
Skewness	0.853063	0.479631	0.977157	0.528408	0.712365	0.759386	1.512024	0.92102	0.961938	0.484407	0.741122	0.5859	0.717877	0.714337	0.950951	0.826687	0.968553	0.480827	1.000079	0.546189	0.614434	0.754074	1.389322	0.937637
Kurtosis	2.846338	2.147577	3.201908	2.269737	2.583837	2.612012	5.283388	2.821265	3.198149	2.164598	2.864058	2.387439	2.64052	2.643405	3.391018	2.669451	3.166938	2.154726	3.295513	2.31225	2.408158	2.617942	4.825757	2.848308
Maximum	0.034027	0.152714	0.027272	0.031951	0.045973	0.052503	0.171557	0.043542	0.019272	0.058469	0.013853	0.018528	0.020622	0.023151	0.034389	0.022866	0.041129	0.137598	0.04217	0.036671	0.058069	0.061984	0.105962	0.062918
Minimum	0.020216	0.048833	0.018341	0.02159	0.024338	0.025238	0.037349	0.027009	0.012747	0.023266	0.01109	0.013624	0.014001	0.014829	0.016298	0.016354	0.025734	0.05064	0.028735	0.026978	0.034271	0.031574	0.03117	0.030814
lquartile	0.021999	0.059791	0.018627	0.022912	0.026498	0.028956	0.049289	0.028738	0.013486	0.026851	0.011179	0.014279	0.014553	0.015894	0.019022	0.017168	0.027623	0.059506	0.029103	0.028236	0.037853	0.035686	0.038329	0.034966
uquartile	0.027113	0.11351	0.022077	0.028462	0.036749	0.043295	0.094351	0.035656	0.016174	0.045051	0.012605	0.016569	0.017652	0.01996	0.025791	0.020412	0.033701	0.104652	0.034335	0.033219	0.047948	0.05181	0.064132	0.045267
upercentile	0.031926	0.145721	0.025427	0.031193	0.042256	0.048267	0.119552	0.041642	0.018224	0.055926	0.013196	0.017936	0.019998	0.022133	0.030209	0.022496	0.038926	0.131705	0.039235	0.035724	0.058062	0.057456	0.079107	0.057519
lpercentile	0.020216	0.048833	0.018341	0.02159	0.024338	0.025238	0.037349	0.027009	0.012747	0.023266	0.01109	0.013624	0.014001	0.014829	0.016298	0.016354	0.025734	0.05064	0.028735	0.026978	0.034271	0.031574	0.03117	0.030814
Botton	0.021999	0.059791	0.018627	0.022912	0.026498	0.028956	0.049289	0.028738	0.013486	0.026851	0.011179	0.014279	0.014553	0.015894	0.019022	0.017168	0.027623	0.059506	0.029103	0.028236	0.037853	0.035686	0.038329	0.034966
2Q	0.00245	0.021652	0.001864	0.002345	0.003484	0.005128	0.00903	0.002065	0.001085	0.007043	0.000687	0.001135	0.001478	0.001824	0.001243	0.001118	0.002314	0.017859	0.002782	0.002272	0.00327	0.005868	0.004144	0.001852
3Q	0.002663	0.032068	0.001587	0.003204	0.006767	0.009211	0.036031	0.004853	0.001603	0.011156	0.000739	0.001155	0.001621	0.002241	0.005526	0.002126	0.003764	0.027286	0.00245	0.002711	0.006825	0.010255	0.021659	0.008449
W+	0.004813	0.032211	0.003349	0.002731	0.005508	0.004971	0.025202	0.005986	0.00205	0.010875	0.000591	0.001367	0.002346	0.002174	0.004417	0.002084	0.005226	0.027053	0.0049	0.002505	0.010114	0.005646	0.014976	0.012251
w-	0.001783	0.010958	0.000286	0.001323	0.00216	0.003718	0.011941	0.001729	0.000739	0.003585	8.88E-05	0.000655	0.000552	0.001065	0.002725	0.000814	0.001889	0.008866	0.000368	0.001257	0.003582	0.004112	0.007158	0.004153

Tab. 8: Numeric LCA-MCS results for WES (Wind energy support) and the three recipe endpoints

	WES																							
	LFP	NaS	LTO	NCA	NCM	NaNiCl	VRLA	RFB	LFP	NaS	LTO	NCA	NCM	NaNiCl	VRLA	RFB	LFP	NaS	LTO	NCA	NCM	NaNiCl	VRLA	RFB
	DRA	DRA	DRA	DRA	DRA	DRA	DRA	DRA	DE	DE	DE	DE	DE	DE	DE	DE	DHH	DHH	DHH	DHH	DHH	DHH	DHH	DHH
Mean	0.006304	0.008634	0.00487	0.00686	0.008233	0.009398	0.027365	0.013035	0.002106	0.002746	0.001151	0.00218	0.002375	0.002548	0.003905	0.004135	0.007202	0.008636	0.008379	0.007028	0.012712	0.010804	0.016654	0.021606
Standard error	0.000216	0.000331	0.000375	0.000345	0.000605	0.00062	0.001739	0.000879	8.81E-05	0.000112	6.41E-05	0.000115	0.000178	0.000161	0.000213	0.000287	0.000254	0.000279	0.00036	0.000288	0.000848	0.000675	0.000965	0.001668
Median	0.00606	0.008604	0.004918	0.006326	0.007558	0.008018	0.025332	0.012126	0.001973	0.002718	0.001132	0.001992	0.002175	0.002206	0.003679	0.003841	0.006729	0.008601	0.007588	0.00657	0.012285	0.009308	0.015613	0.020036
Standard deviation	0.000965	0.001482	0.001678	0.001542	0.002708	0.002774	0.007775	0.003931	0.000394	0.000501	0.000287	0.000516	0.000797	0.000718	0.000954	0.001284	0.001136	0.001247	0.00161	0.001286	0.003793	0.003019	0.004316	0.00746
Variance	9.3E-07	2.2E-06	2.81E-06	2.38E-06	7.33E-06	7.7E-06	6.05E-05	1.55E-05	1.55E-07	2.51E-07	8.21E-08	2.66E-07	6.36E-07	5.16E-07	9.09E-07	1.65E-06	1.29E-06	1.56E-06	2.59E-06	1.65E-06	1.44E-05	9.11E-06	1.86E-05	5.56E-05
Skewness	0.573184	2.032561	0.037682	0.450733	2.45296	0.988568	0.739128	2.205286	0.719483	2.053784	0.166316	0.450595	2.498411	0.997111	0.739306	2.23374	0.713383	1.9689	1.245419	0.443302	1.901338	0.988324	0.732182	2.276506
Kurtosis	2.139416	8.380748	2.278273	1.992483	9.55618	2.83464	2.631412	8.764826	2.542658	8.407265	2.356213	1.983487	9.74927	2.852613	2.662034	8.870471	2.466414	8.204985	3.454027	1.996607	7.297092	2.836353	2.628007	9.042514
Maximum	0.008083	0.01391	0.008048	0.009541	0.018246	0.015312	0.045134	0.027241	0.003037	0.004532	0.001699	0.003079	0.00534	0.004062	0.006107	0.008789	0.009824	0.013049	0.012349	0.009261	0.025727	0.017233	0.026514	0.048791
Minimum	0.004849	0.006829	0.002405	0.004678	0.005846	0.006376	0.017968	0.008773	0.00162	0.002147	0.000731	0.001452	0.001633	0.001765	0.002772	0.002754	0.005759	0.007082	0.006842	0.005199	0.008782	0.00751	0.011482	0.013639
lquartile	0.005487	0.00728	0.002546	0.005486	0.006413	0.00691	0.020121	0.01014	0.001719	0.002293	0.000775	0.001714	0.001815	0.001898	0.002986	0.0032	0.006169	0.007457	0.007242	0.005887	0.009566	0.008085	0.012556	0.016133
uquartile	0.006928	0.009063	0.006426	0.008106	0.009087	0.010868	0.033586	0.014422	0.0024	0.002907	0.001424	0.002619	0.0026	0.002912	0.004675	0.004598	0.008094	0.00898	0.009883	0.00805	0.013968	0.012399	0.020124	0.024352
upercentile	0.007966	0.009923	0.007818	0.009527	0.011147	0.01507	0.042501	0.016595	0.002707	0.003194	0.001691	0.00307	0.003177	0.004053	0.005752	0.005299	0.008987	0.009727	0.011994	0.009246	0.017537	0.017	0.025056	0.028369
lpercentile	0.004849	0.006829	0.002405	0.004678	0.005846	0.006376	0.017968	0.008773	0.00162	0.002147	0.000731	0.001452	0.001633	0.001765	0.002772	0.002754	0.005759	0.007082	0.006842	0.005199	0.008782	0.00751	0.011482	0.013639
Botton	0.005487	0.00728	0.002546	0.005486	0.006413	0.00691	0.020121	0.01014	0.001719	0.002293	0.000775	0.001714	0.001815	0.001898	0.002986	0.0032	0.006169	0.007457	0.007242	0.005887	0.009566	0.008085	0.012556	0.016133
2Q	0.000573	0.001324	0.002372	0.000841	0.001145	0.001108	0.005211	0.001986	0.000255	0.000426	0.000357	0.000278	0.000361	0.000308	0.000693	0.000641	0.00056	0.001144	0.000346	0.000683	0.002719	0.001224	0.003056	0.003904
3Q	0.000868	0.000459	0.001508	0.001779	0.001529	0.00285	0.008254	0.002296	0.000426	0.000188	0.000292	0.000627	0.000425	0.000706	0.000997	0.000757	0.001366	0.000379	0.002295	0.00148	0.001683	0.00309	0.004511	0.004315
W+	0.001038	0.00086	0.001392	0.001421	0.00206	0.004202	0.008916	0.002173	0.000307	0.000287	0.000267	0.000451	0.000577	0.001141	0.001077	0.000702	0.000893	0.000747	0.002111	0.001196	0.003569	0.004601	0.004932	0.004018
w-	0.000638	0.000452	0.000141	0.000808	0.000567	0.000534	0.002154	0.001368	9.94E-05	0.000145	4.4E-05	0.000263	0.000182	0.000133	0.000214	0.000446	0.00041	0.000375	0.0004	0.000688	0.000785	0.000574	0.001074	0.002494

Tab. 9: Numeric LCA-MCS results for HMGS (hybrid micro grid system) and the three recipe endpoints

	HMGS																							
	LFP	**NaS**	**LTO**	**NCA**	**NCM**	**NaNiCl**	**VRLA**	**RFB**	**LFP**	**NaS**	**LTO**	**NCA**	**NCM**	**NaNiCl**	**VRLA**	**RFB**	**LFP**	**NaS**	**LTO**	**NCA**	**NCM**	**NaNiCl**	**VRLA**	**RFB**
	DRA	**DRA**	**DRA**	**DRA**	**DRA**	**DRA**	**DRA**	**DRA**	**DE**	**DE**	**DE**	**DE**	**DE**	**DE**	**DE**	**DE**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**	**DHH**
Mean	0.00695	0.015298	0.005572	0.007028	0.009789	0.010467	0.0293	0.009745	0.003971	0.006858	0.002808	0.004034	0.004528	0.00476	0.006456	0.00499	0.007738	0.014074	0.008207	0.00712	0.014037	0.011751	0.018126	0.015254
Standard error	0.000266	0.000952	0.000201	0.000357	0.000585	0.000689	0.00165	0.000474	0.000113	0.000337	6.69E-05	0.000148	0.00017	0.000193	0.000221	0.000156	0.000278	0.000803	0.000313	0.000307	0.000817	0.000745	0.00091	0.000929
Median	0.006473	0.013826	0.005198	0.006595	0.008841	0.009639	0.026898	0.008973	0.003755	0.006381	0.002716	0.003819	0.004271	0.004511	0.006137	0.004733	0.007194	0.012804	0.007697	0.006625	0.012482	0.010943	0.016927	0.013693
Standard deviation	0.001188	0.004257	0.000901	0.001597	0.002617	0.003083	0.00738	0.002121	0.000506	0.001506	0.000299	0.00066	0.000762	0.000863	0.000987	0.000697	0.001242	0.00359	0.001401	0.001374	0.003653	0.00333	0.004069	0.004157
Variance	1.41E-06	1.81E-05	8.11E-07	2.55E-06	6.85E-06	9.51E-06	5.45E-05	4.5E-06	2.56E-07	2.27E-06	8.96E-08	4.36E-07	5.8E-07	7.45E-07	9.75E-07	4.86E-07	1.54E-06	1.29E-05	1.96E-06	1.89E-06	1.33E-05	1.11E-05	1.66E-05	1.73E-05
Skewness	0.595029	1.508659	0.842842	0.847758	1.185137	1.027605	0.724266	1.023334	0.528723	1.331462	0.044529	0.704628	1.012185	0.409888	0.698792	0.555117	0.77945	1.520515	0.791345	0.830787	1.287722	0.936437	0.717731	1.031598
Kurtosis	2.208989	4.741495	3.050747	2.961224	3.690968	3.22789	2.339152	2.696656	2.136625	4.177747	1.846632	2.820735	3.272532	2.305458	2.421018	1.845166	2.181222	4.803633	2.757915	2.904214	4.223322	3.005077	2.354306	2.60591
Maximum	0.009514	0.027936	0.007649	0.011084	0.016947	0.018084	0.044343	0.014651	0.004954	0.011168	0.003327	0.005607	0.006461	0.006415	0.008607	0.006235	0.010265	0.024824	0.011448	0.010527	0.024603	0.019841	0.026369	0.02447
Minimum	0.005352	0.010779	0.004354	0.005015	0.006665	0.006022	0.019848	0.007473	0.003209	0.0051	0.002297	0.002999	0.003523	0.003198	0.004983	0.004049	0.006393	0.010336	0.006436	0.005339	0.009773	0.006881	0.012807	0.011064
lquartile	0.005983	0.012236	0.004893	0.005631	0.007833	0.008288	0.023198	0.008116	0.00353	0.005678	0.002558	0.003585	0.003846	0.004037	0.005742	0.004349	0.006628	0.011435	0.00714	0.00605	0.011416	0.009383	0.014946	0.011941
uquartile	0.007896	0.017303	0.006237	0.008324	0.012045	0.011924	0.033586	0.011399	0.00457	0.007797	0.003086	0.004458	0.004947	0.005476	0.007483	0.005783	0.009212	0.015793	0.009153	0.008242	0.015707	0.013782	0.020613	0.018296
upercentile	0.00897	0.022974	0.007529	0.00952	0.014437	0.016414	0.041785	0.013322	0.004905	0.009285	0.003256	0.005113	0.005991	0.006373	0.008087	0.006073	0.010039	0.020141	0.011002	0.00951	0.019655	0.017921	0.02495	0.022671
lpercentile	0.005352	0.010779	0.004354	0.005015	0.006665	0.006022	0.019848	0.007473	0.003209	0.0051	0.002297	0.002999	0.003523	0.003198	0.004983	0.004049	0.006393	0.010336	0.006436	0.005339	0.009773	0.006881	0.012807	0.011064
Botton	0.005983	0.012236	0.004893	0.005631	0.007833	0.008288	0.023198	0.008116	0.00353	0.005678	0.002558	0.003585	0.003846	0.004037	0.005742	0.004349	0.006628	0.011435	0.00714	0.00605	0.011416	0.009383	0.014946	0.011941
2Q	0.00049	0.00159	0.000305	0.000964	0.001008	0.00135	0.0037	0.000857	0.000224	0.000704	0.000158	0.000233	0.000425	0.000474	0.000394	0.000384	0.000567	0.001368	0.000557	0.000575	0.001066	0.00156	0.001981	0.001752
3Q	0.001423	0.003476	0.00104	0.001729	0.003204	0.002285	0.006688	0.002426	0.000815	0.001416	0.00037	0.00064	0.000676	0.000965	0.001346	0.00105	0.002018	0.002989	0.001456	0.001618	0.003225	0.002839	0.003686	0.004604
W+	0.001075	0.005671	0.001292	0.001196	0.002392	0.00449	0.008199	0.001923	0.000335	0.001488	0.00017	0.000654	0.001044	0.000897	0.000604	0.000291	0.000827	0.004348	0.001849	0.001268	0.003948	0.004139	0.004337	0.004375
w-	0.000631	0.001457	0.000539	0.000616	0.001168	0.002266	0.00335	0.000644	0.000321	0.000578	0.000261	0.000586	0.000322	0.000838	0.000759	0.000299	0.000234	0.001099	0.000704	0.000711	0.001643	0.002502	0.002139	0.000877