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Manuel Johann Baumann
(email: manuel.baumann@kit.edu)

A Constructive Technology Assessment of Stationary Energy Storage Systems: prospective Life Cycle orientated Analysis

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Faculdade de Ciências e Tecnologia
Universidade Nova de Lisboa
Monte de Caparica
Portugal

FACULDADE DE CIÊNCIAS E TECNOLOGIA UNIVERSIDADE NOVA DE LISBOA

A Constructive Technology Assessment of Stationary Energy Storage Systems

prospective Life Cycle orientated Analysis *

Manuel Johann Baumann

Supervisors: Dr.-Ing. Marcel Weil
Prof. Dr. António Brandão Moniz

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Abstract:

Environmental concerns over the use of fossil fuels and their resource constraints have increased the interest in generating electric energy from renewable energy sources (RES) to provide a sustainable electricity supply. A main problem of those technologies (wind or solar power generation) is that they are not constant and reliable sources of power. This results inter alia in an increased demand of energy storage technologies. Related stake holders show a big interest in the technical, economic and ecologic aspects of new emerging energy storage systems. This comes especially true for electrochemical energy storage systems as different Li-Ion batteries, Sodium Sulfur or Redox Flow batteries which can be utilized in all grid voltage levels, a wide range of grid applications as well as end user groups (e.g. private households, industry). A prospective and active Constructive Technology Assessment (CTA) can help to minimize potential mismatches, wrong investments, possible social conflicts, and environmental impacts of new energy storage technologies in an early development stage. It is insufficient to exclusively look at the operation phase to assess a technology. Such an approach can lead to misleading interpretations and can furthermore disregard social or ecological impact factors over the whole life cycle. Different energy storage technologies have to be evaluated in a prospective manner with a full integrated sustainability and life cycle approach to form a base for decision making and to support technology developers in order to allow distinctions between more or less sustainable battery technology variations. Therefore CTA is used as a scientific approach using several "neighbouring" engineering orientated disciplines e.g. Life Cycle Analysis (LCA), Social Life Cycle Assessment (SLCA) or Life Cycle Costs (LCC) and their methodologies which were initially developed for other purposes.

The aim of the presented PhD Thesis is to make an economic, technological and ecological comparison of Energy storage technologies based on a life cycle sustainability Analysis (LCSA), multi criteria Analysis (or evaluation) (MCA) and to develop a suitable LCSA-MCA model through a new combined highly interdisciplinary approach in frame of CTA.

Key words: renewable energy, electric energy, energy storage technologies, Life Cycle Analysis, Constructive Technology Assessment, sustainability

JEL codes: O44, Q42, Q55, R49

Content

1. Introduction

The *Leitbild* of sustainable development is nowadays a major issue in public debate and scientific research [1]. Especially the global energy sector is currently undergoing a paradigm change towards increased sustainability. Scarcity of fuels, changes in environmental policy and changes in society increased the interest in generating electric energy from renewable energy sources (RES) [2]. This development includes a severe transformation of the electricity infrastructure as a socio-technical system, representing a considerable challenge for countries which have achieved a high standard of energy supply [1].

This comes especially true for Germany with its ambitious target to produce 35 % of the needed electricity from renewable energy systems by 2020 and over 80 % up to 100 % by 2050 within the so called “Energiewende” - Energy transition [3] which is flanked by the German government. The main problem of the most relevant RES solar and wind energy is that they cannot supply constant power output. As a consequence of this development significant challenges for grid operators occur which have to compensate the variability of an increasing share of decentralized solar and wind power to maintain grid stability as well as security of supply [4]. This results inter alia in an increased demand of backup technologies as energy storage technologies to assure system safety [4]. There are several technologies available for multiple time dimensions as Pumped Hydro Electric Power Plants, Power to Gas, Compressed Air Energy Storage and Battery Systems. All available technologies have their own technical, environmental and societal characteristics allowing them to fulfil different requirements or applications fields respectively.

Big technical developments were achieved in the field of battery storage technologies in the last years [5]. A major advantage of batteries in relation to large scale energy storage technologies is that they do not have any special requirements regarding geology (e.g. height difference for PHE or salt/impervious rock caverns as well as aquifers for CAES), a high modularity, flexibility and high efficiency grades. Existing studies often focus on decentralized applications with power ratings of some kilowatt up to one digit megawatts e.g. the operation of energy storage technologies in combination with wind parks or in standalone power systems [6]. However, there are still research gaps regarding the economic, ecologic and social performance of emerging energy storage systems as battery systems. Therefore, related stake holders within the whole energy value chain show a big interest in the technical, economic and ecologic aspects of energy storage systems and their role in the whole socio-technological transmission of the energy system.

2. Problem specification and Research question

In the following chapters the problem with the resulting research question will be presented briefly. Furthermore the hypothesis and approach will be discussed.

2.1 Problem introduction

The fast changing electricity sector can be considered as a socio-economic system strongly embedded in the life of individuals, companies and policy making. It is based on a seamless web of related highly heterogenic factors which underlie dynamic new switch stands [5]. Inter alia acceptance, social issues, industrial dynamics, governance, control and power are also main elements [1] that influence the outcome of a new technology. There are several heterogenic factors within a socio-technic system which can generally influence technology development. The energy system is strongly embedded in this system and has a highly complex character. Energy storage systems as a technology play an integral role within the energy system embedded in this complex system.

Technology is always embedded in interdependent subsystems, divided into society, economy and environment. The demand for energy and raw materials, mass flows and materials and infrastructure is strongly determined by technology [7]. The development, production, use, profitability, environmental impact, user acceptance and disposal of energy storage technologies have a major importance for a sustainable energy system development and must therefore be co-considered in the transformation of the energy system [8]. Figure 1 gives an overview of the subsystems in hierarchical perspective with their interdependencies.

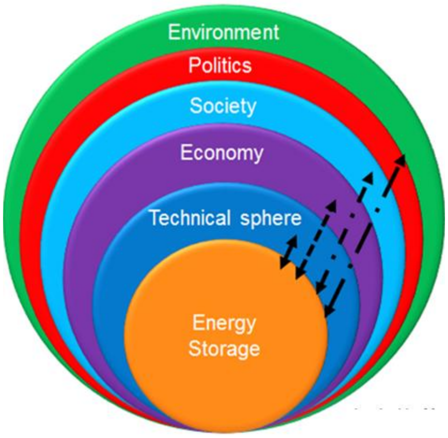

Figure 1: Holistic system perspective on electrochemical storage systems (own figure inspired by **[7]** and **[9]**)

It is insufficient to exclusively look at the operation phase of energy storage technologies. This can lead to misleading interpretation and disregards social or ecological impact factors over the whole life cycle of a product. In the optimum a product life cycle should have a balancing of relevant sustainability factors as ecology, society and economy [10]. Emerging energy storage technologies have to be assessed in a prospective manner to shape them more sustainable before they enter into market. This requires a prospective Life Cycle orientated assessment: production patterns, political as well as economic framework conditions, future developments and markets and usage of technologies are some examples for aspects that have to be considered in order to support a sustainable development of technology.

2.2 Research question

The general question is, if energy storage technology development and the application of resulting products can be organized in sustainable or at more sustainable manner [10]? The aim of this thesis is therefore to develop and investigate the applicability of a new scientific-technological progress in order to shape the development and right choice of energy storage technologies in concordance with sustainability principles in an early stage of development via a methodology based on constructive technology assessment (CTA) by the use of life cycle assessment methods, multi criteria evaluation (MCA) and a parallel stakeholder mapping. The focus of the research will be on energy storage technologies but will also include other storage options for comparison reasons. The challenge is how to combine the different approaches, simplify them and to minimize data requirement as well as data uncertainty. A main challenge is to conduct this assessment in a prospective way for early technology shaping and to involve relevant stakeholders. The research question resulting from those challenges can be formulated as following:

How to evaluate different stationary energy storage technologies in a prospective manner with a full integrated life cycle model – CTA approach to form a base for technology developer support and decision making?

For this reason a model based approach is chosen in steadily exchange with stakeholders to solve the before mentioned problem by fulfilling the following methodological requirements:

- Evaluate future energy storage demand and implications for energy storage technologies through changing market and electricity system conditions
- Description and reproduction of technical, environmental and economic properties of energy storage systems under defined energy market conditions
- Involve stakeholders for prospective technology evaluation by defining technologies, target values and maintain iterative exchange during the whole assessment
- Additional institutional inertia in the uptake of new technologies during a technological transition is often an underestimated factor which should be included as a side task in this work. Comparing different cases in form of a brief overview could help to overcome potential regulatory obstacles and to identify best practice examples for the German case.

2.3 Hypothesis and approach

Technology Assessment (TA) has been developed initially as an approach first to explore possible unintended and negative side-effects of emerging technologies, to elaborate strategies for dealing with them and to provide policy advice [1]. It is traditionally more focused on external effects and the choice of different technology options [2]. There exist several forms of TA, representing various sets of basic approaches which are adopted to specific conditions and technologies with the aim of improving the societal embedding of those [3]. Within the different paths of Technology Assessment (TA) constructive technology assessment (CTA) can be considered to be the best kind to support the development of energy storage technologies in a reflexive way and to compare emerging storage systems [11]. The methodology was developed in the Netherlands by [12] and was adopted or adapted in several European countries [10].

CTA extends traditional technology assessment functions beyond policy-making. It is used to include non-governmental actors, to add the concept of anticipation of future technology developments e.g. electrification of transport [13]. CTA has the expectation of minimizing mismatches, wrong investments, possible social conflicts, and environmental impacts [12] of a new technology in an early development stage. However, different energy storage technologies have to be evaluated in a prospective manner with a full integrated life cycle approach to form a base for decision making and to support technology developers in order to allow distinctions between more or less sustainable energy storage technology variations. Therefore CTA is used as a scientific approach using several “neighbouring” engineering orientated disciplines e.g. Life Cycle Analysis (LCA), Social Life Cycle Assessment (SLCA) or Life Cycle Costs (LCC) and their methodologies which were initially developed for other purposes [14].

Most existing work regarding CTA has a high descriptive character, only partially allowing to actively shaping technology in a prospective way. The use of both descriptive and active engineering approaches can help to assess technologies in a prospective way. Life cycle approaches are a methodology that optimally matches the aim of CTA in an active way by giving detailed information about technical, ecological, societal and economic factors during an entire life cycle of a product to shape or optimize its development. The use of e.g. LCC, LCA can help to compare traditional product systems with a product which contains an innovative component. Comparing both products (traditional vs. innovative) makes it then possible to give a feedback to developers about the specific impact of their innovative product system.

A Life Cycle Assessment perspective is a possibility to assess all mentioned dimensions as well as life phases (from extraction and processing of resources, production etc.) within CTA of a distinct product. It does not only map the contents mentioned dimensions and their crosslinks but also the interactions over the complete life cycle of a specific product or technology (in this case EESS). This represents the most suitable method to carry out an integrated, techno - economic – societal and ecological investigation of EESS over the whole life cycle.

3. Theoretic background

The following chapter has the aim to give a brief overview of relevant changes of the electricity energy system and energy storage systems.

3.1 Renewable energy growth and energy storage demand

An ubiquitary, highly reliable, sustainable and cheap availableness of electric energy is a precondition for economic productivity and life standard of a society. Therefore the EU aims to increase the share of renewable energy sources (RES) to assure security and diversification of energy supply, environmental protection and social and economic cohesion. A first step was done with the Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity from renewable energy sources (non-fossil renewable energy sources such as wind, solar, geothermal, wave, tidal, hydroelectric, biomass, landfill gas, sewage treatment gas and biogas) in the internal European electricity market [15]. In frame of this accession treaty national indicative targets were set for the proportion of electricity produced from RES in each new member state [15]. The share of low carbon technologies in the electricity mix is estimated to increase from around 45% today to around 60% in 2020, including through meeting the renewable energy target, to 75 to 80% in 2030, and nearly 100% in 2050 [16].

As already mentioned in the introduction, Germany aims to produce 35 % of the needed electricity from renewable energy systems by 2020 and over 80 % up to 100 % by 2050 within the so called "Energiewende" - Energy transition [3] which is flanked by the German government. Within this transition solar and wind energy are the most promising technologies among other renewable energy systems providing about 75 % of the required energy in 2050 [17]. The high amount of fluctuating energy sources represents a technical challenge for the German electricity supply system. Stochastic energy productions fluctuations can lead inter alia to temporary capacity problems due to limited correlation of load and generation as depicted in figure 2.

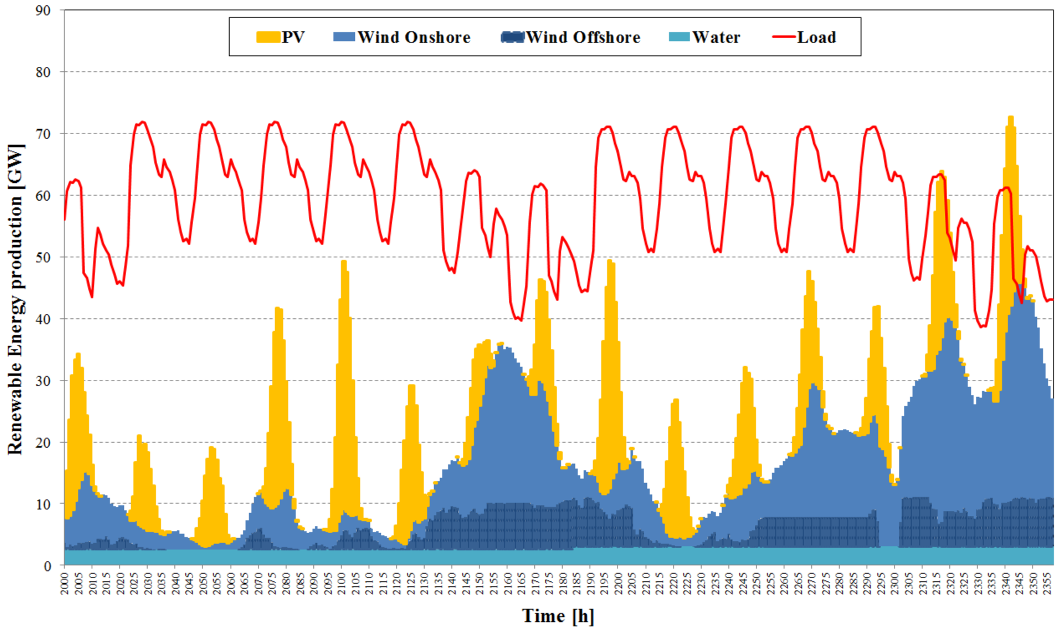

Figure 2: One week in 2023 in Germany (Scenario A - own simulation based on [18], [19], [20], [21], [22], [23] and [24])

A successful integration of renewable energy sources has to be done on different time dimensions covering seconds, hours to days (e.g. seasonal storage or balancing forecast errors). This comes especially true for a future energy system with an increasing share of RES and less possibilities to balance these with conventional power plants [6]. This can cause blackouts if the gaps are not filled by suitable backup technologies as energy storage technologies. The most valuable scenario E [17] of the VDE – ETG Taskforce for Energy storage estimates that the German demand for short term energy storage in 2050 could be up to 14 GW with a needed capacity of 70 GWh. Long term storage demand is even higher with 18 GW and 7 TWh storage capacity [17]. Droste-Franke reports that economic viable storage capacities of in 2040+ could be about 15 GW. However, it is clear that energy storage will play an important role in the future energy system.

3.2 Energy storage systems and typical application fields

It is crucial to analyse available technologies in detail to select the most appropriate technology with regard to demand [25]. Energy storage technologies can generally be divided into mechanical, electrical, thermal and chemical systems as well as hybrid systems. There exists a high quantity of technologies [26] including Advanced Battery Systems (BESS), Pumped Hydro-Electric (PHE), (adiabate) Compressed Air Energy Systems (CAES or A-CAES), Flywheels, Super Conducting Magnet Energy Storage (SMES) and Hydrogen for Energy Storage [27]. Different technologies can also be combined in form of hybrid energy storage devices as for example Liquid hydrogen with superconducting magnetic energy storage (LIQHYSMES) [28]. Most energy storage technologies can cover several application fields in different time, storage and power rating dimensions as depicted in figure 3.

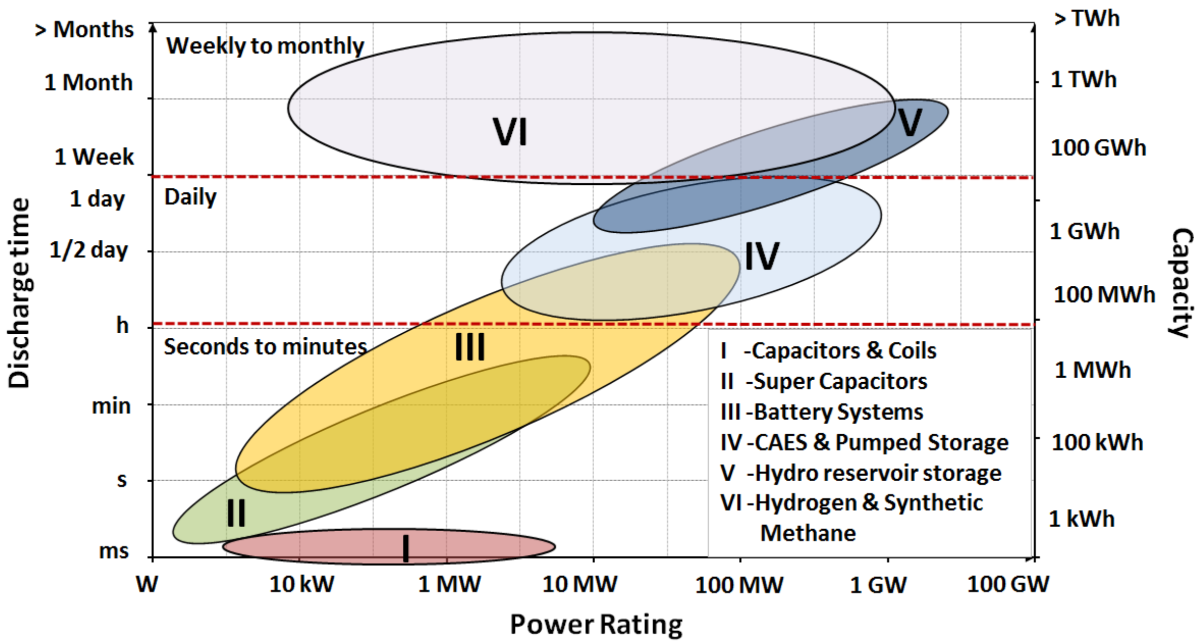

Figure 3: storage and power rating dimensions for different energy storage technologies

Each technology has different performances as well as economic characteristics, application fields and environmental impacts. To regulate frequency, energy storage capacity does not have to last for a long time – seconds to minutes are sufficient combined with a long life time to encounter multiple daily discharge events (e.g. batteries, capacitors or coils). On the contrary load leveling requires multi-MWh energy storage systems that can be discharged over several hours and have a high round trip efficiency as well as a long deep cycle life time (e.g. pumped storage, CAES etc.). All different application possibilities have different cost and technologic tolerances, which finally affect the applicability of different EESS. A brief overview of some available energy storage technologies is presented in the following:

Pumped hydro storage (PHS)

PHS as a mechanical storage system is with a global installed capacity of 129 GW the most mature and important energy storage technology nowadays [26]. A PHS uses cheap energy during low demand times or increased production form RES to pump water into an elevated water reservoir. During peak demand periods, where energy prices usually are higher, water is released from the upper reservoir to generate electricity via hydro turbines, collected in a lower reservoir and to feed it back to the grid [29]. The storage capacity is defined by the height of the fall of water and volume of water available in the upper reservoir. At the same time this variables are the biggest restriction on PHS as suitable sites must have high differences between upper and lower reservoir an enough to build two dams if necessary [26]. Typical installations have power ratings up to 1,000 MW and can provide energy up to 8 hours. Efficiency rates are between 70-80 % [6]. A main drawback of this technology is its high land impact due to the need of the creation of two reservoirs with a high elevation difference and a resulting high capital cost [29]. This restricts the use of PHS in central Europe far away from RES sources as wind to secondary mountain regions or the alps [6].Typically PHS are used for levelling the difference between predicted and actual power generation, ancillary services or energy trading [25].

Compressed air energy storage (CAES)

Another mechanical energy storage technology is CAES which uses as well as PHS cheap energy or energy during low demand times or increased RES production to compress air and to store it under high pressure in an appropriate air storage facility (e.g. underground cavern) [29] [25]. When energy is needed the air is supplied in combination with methane and expanded to a gas turbine [29]. CAES need an extern heating source to preheat the air in a recuperator to avoid icing of the turbines [29]. This heat can be delivered by using the heat of the combustion chamber of the installation (diabatic CAES). Alternative an additionally heat storage can be used (adiabatic A-CAES) to improve efficiency grades from 55 % up to 70 % [25]. There are already two first generation CAES plants in operation (Huntsdorf Germany, 290 MW and Alabama USA, 110 MW) [26]. A-CAES is still in the R&D phase and has not been deployed as a real size system [25]. A consortium of RWE, General Electric, Züblin and DLR planned to build a demonstration site with 90 MW and a 4 hour energy supply nearby Straßfurt in 2013 [6]. Typical plant sizes are comparable with PHS. However, CAES locations are restricted to areas with appropriate geological formations for air storage e.g. in the northern regions of Germany [25].

Electrochemical energy storage technologies

The focus of the study will be on electrochemical energy storage systems. In general batteries convert chemical energy into electric energy. This energy conversion occurs without any intermediate steps, leading to some advantages as high energy efficiency [30]. In general battery cells can be classified into non rechargeable primary cells, rechargeable secondary cells or tertiary cells which are fed continuously to the cell from outside [30]. A major advantage of batteries in relation to large scale technologies (P>100 MW) as PHE and CAES is that they don´t have any special requirements regarding geology (e.g. height difference for PHE or salt/impervious rock caverns as wells as aquifers for CAES) combined with a comparatively little land use impact (e.g. land demand combined with the removal of trees etc.) [5]. Furthermore the have a very high modularity from some kW up to a multi MW level. For grid connection BEES-technologies need power electronics e.g. a bidirectional converter for an AC to DC transformation for charging and DC to AC for feeding back electricity to the grid, which also controls operation mode and grid interface of the BESS. The converter has multiple functions including the assurance that requirements of bidirectional power flow capability are met e.g. a high power factor is reached, reduction of harmonic distortions as well as the regulation of the dc-side battery power regulation [31].

There exist several EESS demonstration projects on a worldwide scale and represent a very dynamic, active research field with various involved institutions. On the one hand BESS are in general a mature technology, which is utilized for more than a century based on industrial products [32]. On the other hand the have many shortcomings in a variety of use cases. The development of secondary batteries for different applications is a challenging task. Batteries have to fulfill simultaneously multiple battery performance requirements such as high power density, a high energy density, long life, low cost, excellent safety, abuse-resistance, a wide bandwidth of operating temperatures and minimal environmental impacts. Nowadays no battery can meet all of these goals, making the right decision of a proper battery system for an special stationary application often a compromise [30]. A good example are Li-Ion based BESS as they are mature in the sense that it is already used widely in several application fields and yet it is immature in the sense that improved performance is demanded for other new applications, such as those in electricity grids [32]. However there are also new high performance cell systems under research, which are far beyond traditional battery systems as NiMH or NiCd or even available Li-Ion cell systems, e.g. Li-Air, Li-Sulfur, or Li/FeFx.

A comparison of different energy storage technologies including two battery systems (Sodium sulfur NAS and generalized Li-Ion battery systems) is given in table 1.

Table 1: Comparison of some energy storage technologies based on [33]

	PHS	**AA-CAES2**	**Li-Ion**	**NaS**
Typical system size	0,1-1 GW	0,1- 0,4 GW	Scalable	Scalable
Energy density	0,7 kWh/m³	2,7 kWh/m³	74-200 Wh/kg	155 Wh/kg
Efficiency	70-80 %	>75 %	70 % -95 %	70 % – 90 %
Cycles	-	-	Ca. 3,000	Ca. 3,300
Cost per kW	600 - 3.000 €/kW	1.000 - 1.500 €/kW	200 - 4.140 €/kW	1.000 – 3.000 €/kW
Cost per kWh	100 – 500 €/kWh	40 - 100 €/kWh	200 – 1.000 €/kWh	210 - 500 €/kWh
Advantages	Mature technology, long operation times	No land use, suitable for large scale application	High energy density, high cost potential	Well-known technology
Disadvantages	Geographic dependencies	Still R&D phase, geographic dependencies	High cost, cycle stability	High temperatures, safety, low power density

It has to mentioned, that not all technologies are available for middle or low voltage levels due to their technological characteristics as for example CAES or pumped hydro storage. A wide field of applications can be covered due to the vertical integration characteristics of modular energy storage systems. This also enables the application of a broad amount of business models including the whole energy value chain from end users, centralized and decentralized energy generation as well as the industry.

3.3 Existing work

There exist several studies about the topic of mobile and stationary energy storage technologies. Most of them handle economic and technical issues of mainly mature technologies. However only a really focus on electro-chemical energy storage systems. Table 2 gives an overview of some studies and their aim. The aim is divided into economic evaluation, environmental impacts, technic evaluation, regulatory framework and multi criteria evaluation. Only Studies which explicitly handle topics regarding energy storage or at least energy topics are mentioned.

Table 2: Literature review considering different aims

Source	Economic Analysis	Environmental Analysis	Technical Analysis	Life cycle perspective	Regulations & Policies	Societal aspects	Multi criteria analysis or evaluation	Research status & Policy	Stakeholder Involvement
[25]	X	X	X	X	X	X		partially	experts
[34]	X		X	partially					
[35]	X		X	partially					
[36]	X		X						
[6]	X		X				X		
[37]	X	X	X	X	X	partially			
[38]	X		X					X	
[39]	X	X	X		X	partially		X	X
[32]	X	Partially	X		Partially	Partially		X	X

As it can be seen almost all of them don´t handle stakeholder issues or conduct a multi-criteria analysis in any form. Life cycle perspectives in the reviewed studies are mostly restricted to life cycle costing approaches. Only 2 Studies cover almost all perspectives and areas. However none has an explicit focus on Battery systems. Of course this selection only represents a small amount of the studies available about the topic of energy storage. Nevertheless none study combined all perspectives including a multi-criteria analysis with stakeholders and actual research status classification of different energy storage technologies.

4. Methodology

The next sections will explain the before briefly mentioned methodology in a detailed manner. This involves technical, ecological, societal and economic factors during an entire life cycle of a product in order to shape or optimize its development.

4.1 Life Cycle Thinking

As presented in chapter 2.3 a life cycle approach will be conducted for the assessment of different energy storage technologies. Life cycle thinking optimally matches the aim of CTA in an active way by assessing technical, ecological, societal and economic factors during an entire life cycle of a product to shape or optimize its development. Several well-known institutions (The World Resource Institute (WRI), the European Commission etc.) as well as many practitioners have adopted life cycle thinking [40].

A full integrative life cycle perspective concept known as life cycle sustainability assessment (LCSA) was developed by [41] is a possibility partially adopted in this approach to assess all mentioned dimensions. The approach involves material, energy and economic flows for all life cycle dimensions of sustainability and helps theoretically to achieve robust results by aggregation as follows [41]:

LCSA = LCA + LCC (+ SLCA not necessarily in life cycle approach)

LCSA	Life Cycle Sustainability Assessment
LCA	Environmental Life Cycle Assessment
LCC	LCA-type Life Cycle Costing
SLCA	Social Life Cycle Assessment

Figure 4 is a schematic illustration of a life cycle perspective covering sustainability requirements (sustainability triangle).

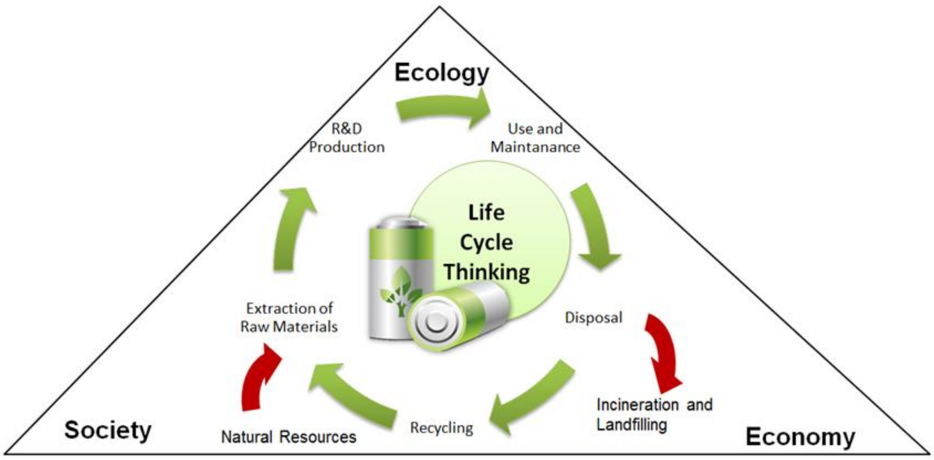

Figure 4: Balance of economic, ecologic and societal activities over a products life cycle **[8]**

Such a prospective LCSA approach can be useful in three practical perspectives:

a) The techno-economic perspective to evaluate possible costs and application possibilities as well as technological developments and paths.
b) The ecologic perspective for e.g. choice of right components or entire technologies regarding their sustainability [42].

c) The societal perspective for e.g. reaction of residents, local added value or contribution to regional development etc.

In general all life cycle approaches subsumed under a LCSA follow in principle the standardized LCA related methodology defined in the ISO 14040. The methodology comprises four phases which are briefly explained in the following based on [43] and which are applied for this work:

a) **Goal and scope definition:** including intended application, reasons for carrying out the study, intended audience, product system to be studied, functional unit, system boundary, data requirements and limitations etc.
b) **Inventory analysis:** Data collection, calculation procedures to quantify relevant inputs and outputs of a product system, allocation of flows and releases
c) **Impact assessment:** evaluation of the significance of potential environmental impacts, maintain transparency
d) **Interpretation:** should deliver results that are consistent with the defined goal scope and which reach conclusions, explain limitations and provide recommondations

The relationship between the phases is illustrated in figure 5 and indicates that all steps have a highly iterative character (black arrows).

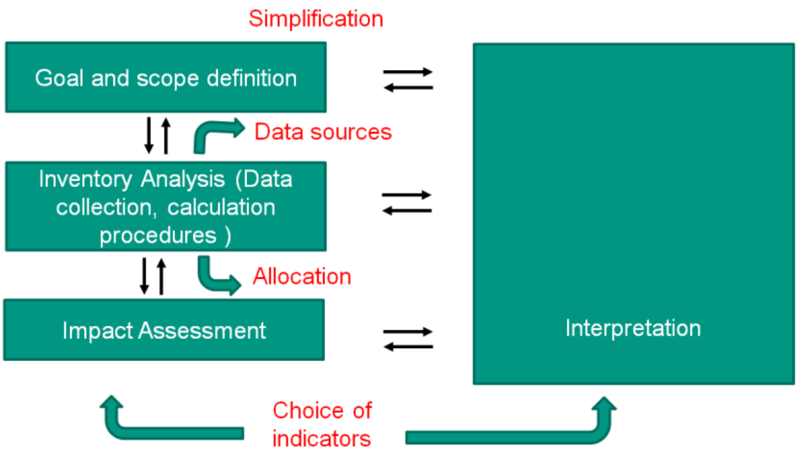

Figure 5: Generalized methodology for life cycle approaches **[43]**

Finally a Multi-criteria Decision Analysis (MCDA) is a possibility to consolidate different category dimensions for one evaluation scale [7]. This makes it possible to compare different energy storage options with each other by the use of a single score. However this step is not of absolute necessity as the specific results already represent a feedback for developers.

In total the academic and case objectives can be listed as followed:

a) Case: evaluate and compare different types of EESS on base of different scenarios
b) Develop a methodology for a LCSA and possibly MCDA model through new or combined already known approaches
c) Generate recommendations for decision making and technology development and support of stakeholders via iterative dialogues (especially for the social dimension).

The assessed CTA-methodology tries to combine this LCSA approach and multi criteria evaluation (MCA). At the same time stakeholders are included to identify technological hot spots or to specify certain target values for calculations.

4.2 Data collection, availability and reliability

After the goal and scope of the study have been defined, the life cycle inventory (LCI) has to be created. The LCI represents all inputs and outputs inside defined system boundaries, including material and energy requirements, emissions, waste, monetary flows and social issues [40]. A solid data base in an absolute precondition for a proper life cycle based assessment of different energy storage technologies to generate accurate results. Average data is already available for a high number of general processes and accessible in open access or proprietary databases as ecoinvent or NEEDS.

An own database for specific techno-economic energy storage technology parameters which are required will be developed. This helps to identify relevant energy storage device parameters, benchmarks as well as related material flows for production and the current development status. Such values can be collected via a comprehensive literature review, interviews or on manufacturing data sheets. The literature review will be based on known sources for scientific papers as Scopus, Science direct and IEEE-Xplore. Interviews could be carried out with battery manufacturing members or scientists/members of the Helmholtz Portfolio project (presented in chapter 4.6.).

For a preliminary comparison available data on efficiency, energy capacity, energy density, run time, capital investment costs, response time, lifetime in years and cycles, self-discharge and maturity of each energy storage system were collected from literature. The collected data showed high deviations of almost all parameter as indicated in figure 6.

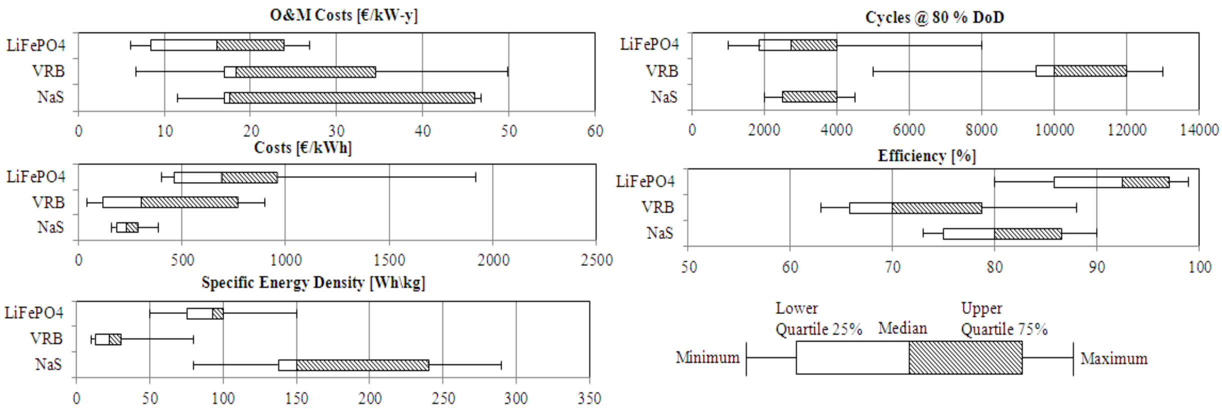

Figure 6: Deviation analysis of techno-economic parameters of different energy storage technologies [2], [4]–[6], [4], [37], [39], [46]–[50]

It can be seen that there are high deviations within scientific literature regarding techno-economic parameters. This makes it difficult to assess technologies as there are high uncertainties. Therefore the methodology has to be adopted to the data situation. The data base forms the integral part of all assessed dimensions.

Another important point regarding literature is to identify further technical development potentials of different technologies to allow a fair comparison (e.g. material savings or more efficient electrodes etc.). Based on the available data, standardized cycles can be used or developed respectively for further calculations and to facilitate an objective multi-criteria comparison and evaluation of different energy storage systems. If possible, different battery degradation models should be used to characterize the life time of a system depending on the application field (e.g. kind of cycling, timeframe etc.).

4.3 Modeling methods

After required data are collected the technology has to be modeled to calculate results [40]. Two frequent problems of prospective LCA and LCC as well as static comparison of emerging technologies is that there is often only a limited amount of data available in combination with a wide value distribution as presented in chapter 4.2. This comes particularly true for technologies with a low or no track record as is the case of some energy storage technologies. This makes it necessary to define specific requirements for an optimal static LCC or LCA comparison method respectively. The method should have a high accuracy related to the amount of input data, low costs and low time expenditure for calculation [51].

A possibility to asses this costs is the analytical combination of different input parameters and to use different scenarios to identify bandwidths of possible price developments as depicted in figure 7.

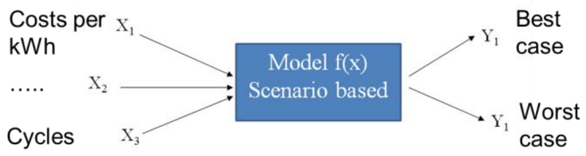

Figure 7: Analytical cost model example for LCC

As depicted in figure 7 a best, worst and base case could be developed to cover possible bandwidths. Such an analytic model or tool has to fulfill in general three standards [42]:

a) The most important factor is the availability and reliability of data for all phases of a life cycle, e.g. ecoinvent, price data, energy scenarios etc.
b) It has to be realistic as well as transparent and has to be based on dynamic frame conditions (energy system, driving behavior) and specific application fields (e.g. frequency and voltage regulation, load leveling etc.)

It has to consider techno-economic-societal and ecological factors over the whole life cycle in a quantitative (e.g. gravimetric and volumetric energy densities, efficiency grades etc.) and if not available somehow qualitative (e.g. acceptance, to a certain degree impact estimation etc.) way.

The problem of analytical approaches is that they don´t give information about variances or distributions respectively. Furthermore a high complexity occurs with an increasing number of assumptions. Probabilistic methods as Monte Carlo simulations (MCS) can solve such complex analytical problems on a simplified numerical base to show bandwiths and uncertainties of cost assumptions. A MCS is used to generate probability values with are afflicted with uncertainties or which are unknown. A precondition for a MCS is the creation of an analytical model as depicted in figure 7. The MCS methodology 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 [52]. This is especially helpful if the analysis of a real system is not or only partially possible [51] as in the case of some storage technologies analysed [33]. In general such a simulation needs reference values and adequate probability functions. A possibility to gather functions and reference values is the involvement of technology developers.

A triangular distribution also known as Simpson distribution as an example could be used for most input data for first calculations, due to the fact that only a minimum x_{min}, maximum x_{max} and most probably value $\bar{x}$ has to be known. This is especially helpful when no good data base is available or values are unknown [33]. The density function of the Simpson distribution can be described by eq. 1.

$$f(x) = \begin{cases} \frac{2(x-x_{\min})}{(x_{max}-x_{min})(\bar{x}-x_{min})} & for\ x_{min} < x < \bar{x} \\ \frac{2(x_{max}-x)}{(x_{max}-x_{min})(x_{max}-\bar{x})} & for\ \bar{x} < x < x_{max} \end{cases} \quad (1)$$

The distribution function as an integral of the density function is described by eq. 2 [51].

$$F(x) = \begin{cases} \frac{(x-x_{min})^2}{(x_{max}-x_{min})(\bar{x}-x_{min})} & for\ x_{min} < x < \bar{x} \\ 1 - \frac{(x_{max}-x)^2}{(x_{max}-x_{\min})(x_{max}-\bar{x})} & for\ \bar{x} < x < x_{min} \end{cases} \quad (2)$$

The Simpson distribution is a plausible approach for computing required parameters [33] in combination with a scarcity of data. Other relevant distribution functions could be the beta-pert, log-normal, normal or beta distribution. Finally all used distribution functions have to be combined to receive a final distribution. Furthermore, a MCS model requires a proper number of simulations (> 1,000) to achieve a distinctive accuracy [53]. An overview of the entire planned MCS methodology is given in figure 8.

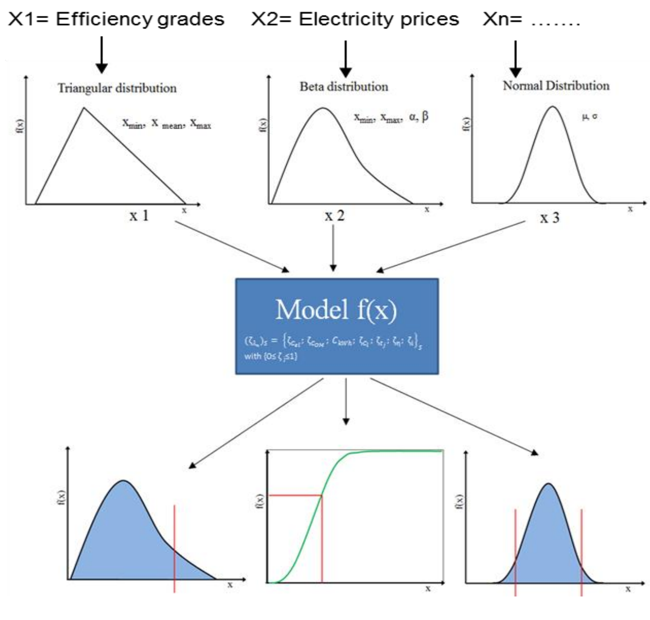

Figure 8: Scheme of a MCS in combination with an analytic model [18]

The results in form of histograms, summary statistics or confidence intervals can be used for analyzing different battery technologies and possible development paths. Such a model could give information about tendency of costs or the variance of environmental impacts.

4.4 Scenario building and application choice

The life cycle approach is based on the mentioned standardized (yearly) cycles and the different fields of application respectively and technology parameters, using different dynamic integration scenarios. After the technical classification and review, different relevant, preponderance application fields (e.g. frequency and load control, renewable energy farming etc.) are briefly analyzed and characterized by preferably using real time measured values (specified by application field, amount of cycles and finally time resolution) [4]. This is important as the criteria for energy storage systems (energy density, power density etc.) are the same for different applications but priorities can be significantly different [54]. Based on the available data, standardized cycles are used or developed for further calculations and to facilitate an (potential) objective multi-criteria comparison and evaluation of different energy storage systems. However, energy storage devices provide a broad field of application solutions along the entire value chain of the electrical system, from transmission and distribution support to generation support to end-customer uses [55]. This makes it necessary to find the right technology for a certain application. The requirements of an application field can be matched with the techno-economic properties of an energy storage technology type to build application scenarios for a comparison of different battery technologies. This helps to identify or rank the best matching technologies for a certain application field.

4.5 Life Cycle Costing

The economic performance is an important approximation for the future and existence of a technology [40]. There are several competing energy storage technologies under the frame of a liberalized European energy market leading to the question which technology is the most economic valuable alternative for its specific application field. Nowadays initial investment decisions are mainly determined by the electricity conversion costs of a technology (life cycle costs - LCC) in €ct./kWh. Energy conversion costs / Life cycle costs include all costs that occur during the whole life time of an asset in €ct./kWh (allready broadly used for power plants). Those costs are divided in capital expenditure (CAPEX), operational expenditure (OPEX) and en of life expenditure (OELEX).

The related full cost accounting calculation includes a dynamic annuitant life cycle cost assessment, which typically only contains negative values (Investment, maintenance, electricity-“fuel price”, annualized capital costs etc.) [56][57]. The method is based on the net present value method NPV which is briefly described in formula 1:

$$C_{NPV} = -I_{t0} + \sum_{t=0}^{T} C_p(1+i)^{-t}$$

Cp = All costs over life time €
It0 = Initial investment costs [€]
i = discount rate i [%]
T = time series [a]

The NPV represents a value calculated from series of payments t which are discounted to the time series t=0 (start of operation of asset). All costs are transferred to a present value t0 (start of operation of asset) and become comparable in a present time dimension. It_0 are calculated by formula 2.

$$I_{t0} = i_p \times \mathrm{P} + i_c \times C + I_C$$

ip = specific power investments [€/kW]
P = rate Power [kW]
ic = specific capacity investments [€/kWh]
C = total capacity [kWh]

Ic = non-specific investments

Another aspect that has to be considered for a fair comparison is possible future price regressions. It has to be mentioned that cost estimates eventually must be considered as preliminary. As already mentioned before the result of this economic assessment is the specific storage costs (€/kWh) of the whole life cycle of each considered technology. Based on this, different EESS may be evaluated with respect to their integration into existing electricity and transport systems allowing for recommendations in battery technology or in a wider scope the whole energy system development. For a fair comparison learning curves shall be used to show potential cost reductions. This makes it possible to estimate the cost reduction potential of different energy storage technologies. An example is that a technology as PHS which is probably at the end of its learning curve shows low cost reduction potentials in relation to certain emerging battery technologies which are at the beginning of their learning curve.

4.6 Life Cycle Assessment - LCA

To assess the environmental attributes of energy storage technologies it is crucial to identify the significant environmental aspects related to the life cycle of a product [58] within a short period of time. A suitable approach to face this challenge is a life cycle assessment (LCA- defined in ISO 14040 and 14044), considering the whole life cycle of a product (cradle to grave analysis). LCA is a well established methodology widely used and has taken a prominent role in environmental policy making [40]. The principle of such an LCA with its system boundaries is given in figure 9.

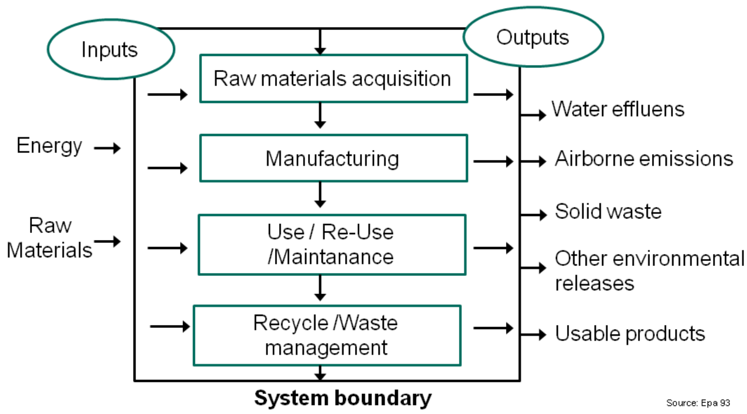

Figure 9: Scheme of a LCA

A full scale LCA study is very detailed, potentially expensive and time consuming and would exceed this study [59]. Therefore a simplified Life Cycle Assessment also called streamlined Life Cycle Assessment involving less cost, time and effort, but yet providing results to complex exercises [60] will be carried out. The main problem of a LCA is to identify the areas which can be omitted or simplified without affecting the results to a certain degree. Consequently different life cycle levels can be excluded by estimating their impact or substituting them by external databases respectively [59]. Within this LCA approach for different applications, only the use phase has to be changed to generate utilizable data. Such a LCA is useful for new eco-innovation when developing a new product like advanced EESS or methods where environmental considerations play a major role from the beginning [59]. Possible indicators within a LCA are ozone depletion, acidification, ionizing radiation or climate change etc. It is appropriate to use a dedicated software to conduct a LCA. For this assessment the software OpenLCA from GreenDelta GmbH will be used.

4.1 Societal approach

Social aspects are definitely the most important criteria for people's acceptance of energy systems during the past decades [8]. The assessment of social factors or well-being respectively is relatively new in the file of quantitative impact assessment at product and technology level [40]. The identification or measurement of societal factors or impacts of energy issues (in general) is difficult due to a missing approved theory [61]. So far only a few studies exist on the evaluation of options of energy related aspects in combination with social aspects and their operationalization [62]. Energy storage technologies represent a new technology, making it challenging to evaluate them in a societal way.

Societal aspects represent a crucial factor for the success or failure of distinctive technology [11]. A societal evaluation of energy storage systems could be carried out based on some evaluation factors identified by [61]. Such factors are e.g. availability of infrastructure for disposal and awareness level of risks etc. This comes especially true for energy storage technologies that directly interfere with the public by visual impacts, perceived health and safety concerns etc. [63]. Another approach is the so called social life cycle Assessment (SLCA) which contains factors of production and consumption impacts on workers, local communities, the society and all value chain actors. Due to the fact that social impacts are not measurable in a direct way, a trade-off has to be done, to facilitate the societal approach within this study. This means that the SLCA will only be assessed partially in relevant fields within the application of EESS. The methodology of a SLCA is comparable to the methodology of a LCA. Some indicators proposed and briefly explained by [40] are autonomy, safety, equal opportunity and participation as well as influence.

Inter Alia a main problem of SLCA is, that there is no really standard for it except of guide lines from Society of Environmental Toxicology and Chemistry (SETAC). Additionally there are only a few studies available. Furthermore which impact categories should be included and how should they be measured? Finally the biggest obstacle for this approach is the scarce of quantitative data regarding the social effects of specific products. Therefore quantitative and qualitative research techniques have to be combined to a certain degree.

4.2 Multi-criteria analysis of LCSA results

An understandable, yet comprehensive presentation of the results of a LCSA is a key challenge to choose the right technology. Therefore, a proper evaluation scale has to be found for a comparison of technologies. It should be mentioned that it is difficult to compare the three indicators (environmental, societal and economic) due to their completely different product relations.

This leads to specific integration problems into the product LCSA-MCA model [41] which has to be solved in a proper way. This could be done by a stave system for different scenarios for different applications considering multiple aspects. Thus, all the factors have to be weighted based on their different impacts or importance.

There are several available methods to carry out this procedure which are briefly presented in by [62] and especially for LCSA by [41]. In general the challenges of a MCA regarding a LCSA are as follows:

- The proper weighting of each indicator within each of the three assessed dimensions e.g. to weight global warming potential in a way to make it comparable with cumulated energy demand (same problem with economic and social indicators)

- Weighting among the three dimensions in a LCSA (which dimension has the bigger impact?)

As explained before this s not of absolute necessity as the specific results of the LCC, LCA and LCSA already represent a feedback for developers.

4.3 Stakeholder involvement

An often underestimated factor in modeling approaches is the role of stakeholders. Stakeholder involvement represents one of the core elements of CTA. This comes especially true for energy storage technologies because of a high number of involved stakeholders [63]. Main reason for this is the vertically integrated nature of storage technologies within generation, network and demand, requiring inter-sectoral perspectives [63]. It is intended to combine or contrasting energy storage and energy system modeling with stakeholder perceptions of a socio-technological transition [63]. Furthermore stakeholders can help to define target values for e.g. investment costs, efficiency, energy density etc. for the MCS.

After identification of stakeholders their interactions need to be identified to understand the sociotechnical system of energy storage. An example is the ownership situation for electricity storage devices as e.g. network operators prefer to contract storage devices form so called aggregators due to regulation limitations (so called unbundling of grid, electricity generation and service) which at the same time propose large energy utilities as possible investors [63]. However an identification of stakeholders and are considered important to identify the benefits as well as possible barriers that have to be up taken to avoid market failure (e.g. technological lock-in effects). It is not possible relevant stakeholders in frame of this work. Therefore mainly developers, which also represent the target group of this research, will be consulted.

Preliminary results, scenarios and assumptions can be used to provide input in interactive workshops consisting of the above mentioned relevant actors. This could make it possible to support broader interactions where actors can probe others perspectives. This could ensue in a reflexive articulation and learning processes. [64]

A main question regarding stakeholders is how they can be integrated within the frame of this work? Some possibilities will be listened up in the following:

- Organize an international workshop on CTA/Energy Storage to generate new ideas or to maybe disperse the actual presented approach. A main problem is who should be invited, where to make the workshop and how to get an adequate funding for it?

- Carry out additional interviews can be seen a good method to reach receive additional information. Potential interview partner could be affiliate research related stakeholders of the Portfolio Project (presented in chapter 4.6)

- Make a preliminary survey which helps to gather additional data e.g. from industry, research or other related stakeholders

A main problem involving stakeholders is how to integrate potential qualitative information/input from stakeholders into a quantitative model (equal vaqueness of human feelings and recognitions [8])? Should this information be added to the modeling approach or serve as additional information? Those questions have to be solved before getting into contact with stakeholders.

4.4 Methodology summary

A summarizing and generalized overview of the actual raw methodology is given in figure 10. It should be mentioned again that the actual figure represents a rough first methodological approach for this work.

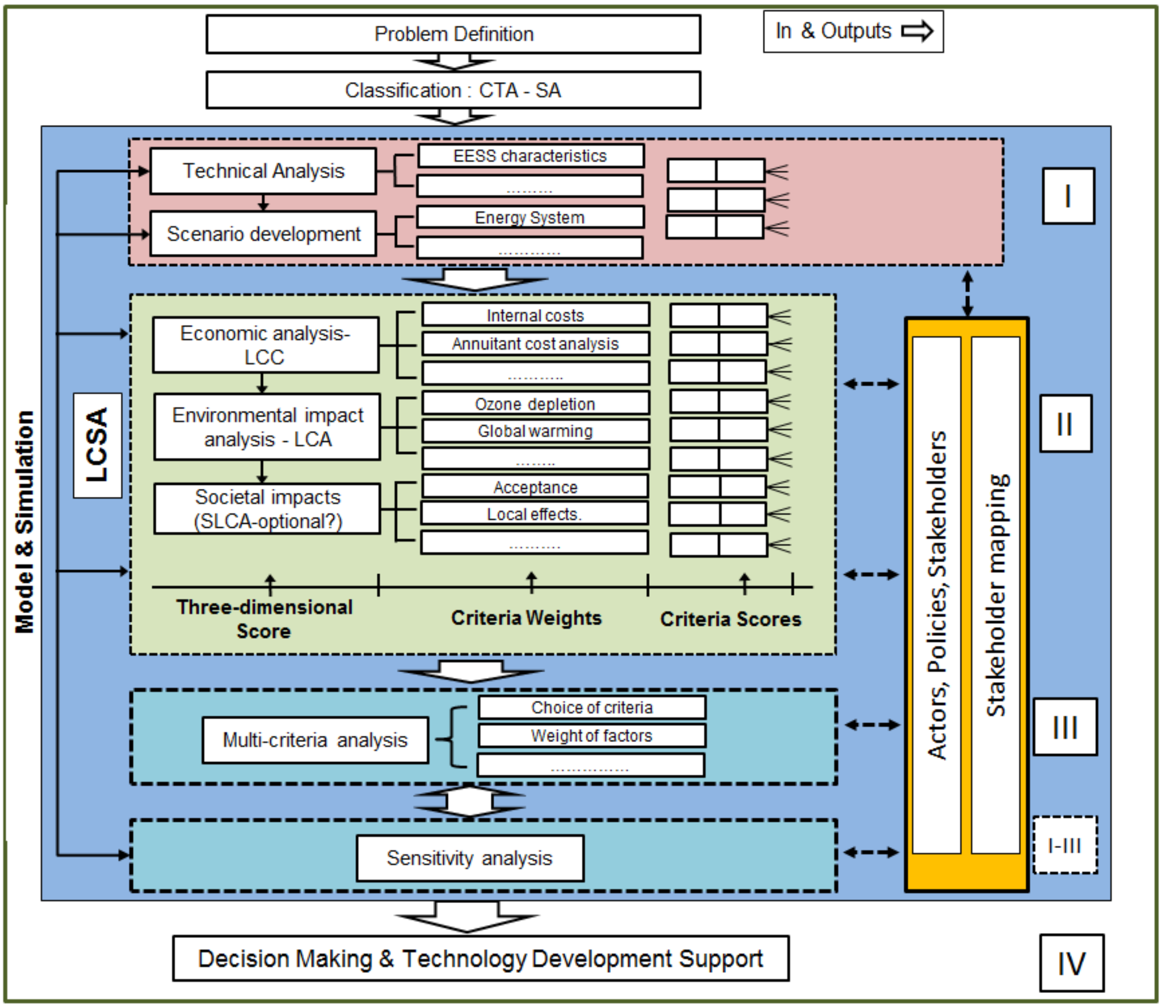

Figure 10: Simplified draft of the planned methodology (Source: own figure inspired by [41] and [62])

The methodology presented in figure 17 can change strongly during the process of the presented PhD project.

4.5 Possible results

The aim of the study is to evaluate different etechnologies depending on several criteria and to generate recommendations for actions via an LCSA-like multi-criteria evaluation approach. The results of the specific dimensions could be as followed:

a) **Technical (integral form in all dimensions):**
   - Identification of the usability of different EESS regarding different application fields
   - technical restrictions and future potentials of EESS
b) **Economical (LCC):**
   - Costs of storage in €/kWh during the whole life cycle via full cost accounting calculation including based on dynamic annuitant life cycle cost assessment
c) **Environmental (SLCA):**

- Different impact factors (KEA, GWP etc.) of EESS via SLCA

d) Societal (S-LCA?):

- Identification of relevant impacts on society

Total (multi criteria analysis of LCSA):

- Evaluation and comparison based on a comprehensive LCSA

The final result is to assist the future development of energy storage technologies by recommendations for further research and development and as a side effect political decision making processes in terms of a constructive Technology Assessment.

4.6 Potential academic claims

The presented word contains several potential academic claims which shall be named briefly. The methodology has a highly interdisciplinary character and it is difficult to estimate if it will work as a combined model or if it is to complex. Furthermore the work has a high anticipatory character as CTA is combined with a more or less sustainability assessment adding more complexity due to high uncertainty reflecting a normative framework, diverse evaluation criteria, prediction challenges, and an need for a comprehensive systemic view [10]. Consequently it could be necessary to conduct a further limitation of technologies, approaches or content in total.

Especially the fields covered by multi-criteria evaluation represent a potential claim as different factors have to be weighted. This represents a problem as far parameters have to be weighted regarding their relevance. If possible this step should be done in an objective way, by using adequate calculation methods. But how for example weight economic against social or environmental parameters? Is there a consensus about e.g. economic and societal criteria within society? Those questions shall be discussed in a higher development status of the research if a MCDA is carried out.

Data availability represents one of the biggest claims as already mentioned in the chapters before. A robust data base represents a precondition which has to be fulfilled for all presented methodological steps within this study. A main question for almost all technologies is if there is any data available? Further challenges regarding data is how to cope with data uncertainties and is it necessary to make certain tradeoffs in respect of the grade of detail of the assessment?

Of course there a several more claims that will occur during the process of work which are not covered here, but they will be considered in the relevant working packages.

4.7 Proposed Time table

The proposed time table represents a first overview of the planned working packages. The time periods and starting points of the single working packages can change during the whole process of research.

Time	Winter semester 2012	Summer semester 2013	Winter semester 2013	Summer semester 2014	Winter semester 2014	Summer semester 2015	Winter semester 2015	Max. expansion time 1 year
Literature review	X	X	X					
Methodology development	X	X						
Data collection		X	X	X	X	X	X	
Analytical LCSA model		X	X					
Stakeholder consultation			X	X				
LCC-Model		X	X	X				
LCA Model		X	X	X				
SLCA-modeling				X	X	X		
Finish thesis							X	?
FCT Courses	Continuously							

5. Integration with other research activities

The supporting institutions in frame of the presented thesis are at first place the UNL-FCT as well as the KIT – ITAS. At the same time the presented thesis will be integrated in the research activities of the Helmholtz association within the portfolio project “Electrochemical energy storage systems – reliability and system integration”. The project has the aim to identify various requirements on electrochemical energy storage technologies within diverse mobile and stationary applications for a specific research and development within multiple levels. This includes a system level view as well as a cell and material level view, regarding the integration and combination of future propulsion systems, entire storage systems with an increased energy density, electrodes, electrolytes or cells. The expertise for this project is provided by the members of Helmholtz association (e.g. Karlsruhe Institute of Technology (KIT), German Aerospace Center (DLR), Research Center Jülich (FZJ)) as well as external partners (RWTH Aachen, TU München etc.) with scientists of multiple areas including diverse engineering fields, economics, social sciences and chemistry [65]. The approach of the Portfolio project focusses on future battery systems (so called 4th generation batteries) whose properties are defined by system requirements of different application fields. This approach helps to define the most suitable battery specifications as well as the related research and development activities.

The portfolio approach includes a broad system analysis with scenario development, safe electrodes development, to minimize innovation risks and identify innovation potentials on all levels and to improve market success of selected electrochemical energy storage technologies. Further aims are to develop new innovative solutions and facilitate the integration to existing technical and economic systems for a successful mobility and energy transition in Germany. The approach includes the use of scenario analysis of application possibilities, integration possibilities of battery systems, techno-economic comparisons of different energy storage possibilities as well as prospective life cycle assessments [65]. The multi perspective project outcomes can be used as a base for future research policy decisions or to estimate to a certain degree the importance of a certain development for the economy including export possibilities.

6. Summary

The presented framework represents a complex approach to minimize negative impacts of energy storage technology options in order to contribute to a sustainable energy system development in an optimal way by using an adopted CTA approach.

In general the maturity of methods and tools which will be used is different for the three dimensions. This comes especially true for social indicators and evaluation methods, which still require fundamental scientific progress. It has to be mentioned that apart from the mentioned challenges of weighting issues, LCSA-like approaches have to deal with the trade-off between validity and applicability.

It also includes several academic claims e.g. the normativity of chosen criteria (consensus about economic and societal criteria within society), multi criteria weighting, epistemic borders of CTA or the simple question if there is even enough data available for a certain type of technology. These problems should also be addressed in a discursive way within this work.

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