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Energy storage systems in the future German electricity system: A foresight approach

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Abstract:

Germany has ambitious targets to produce 35 % of the needed electricity from Renewables mainly based on wind and solar power by 2020 and over 80 % by 2050 within the so called "Energiewende". Energy storage is seen as a potential option to assure the safe RES system integration to achieve these goals. There is a high uncertainty and the resulting public discourse about the future demand and the most suitable type of storage technology is driving further development of these technologies. A literature review of 9 studies and 10 expert interviews are carried out in line of a foresight exercise on to tackle these uncertainties. The estimations of reviewed studies are based models with a market perspective on energy storage demand. Most model-based scenarios are built on top down logics, where processes at lower levels (technology, micro-economic sphere) are determined by dominant macro dynamics. Different technologies are only considered partially or in an aggregated way. The reviewed studies showed that there is a high potential storage on every time scale starting from the year 2030 to 2040. Analysed potentials vary depending on RES diffusion and excess rate assumptions between 0 to 44 GW. Reviewed studies strongly integrate shared visions about system developments and formal analyses and provide important and valuable information about potential future implications. But they only partially account, due to practical reasons, wider benefits, stakeholder opinions and continuous changes. They account also discontinuities in the technological innovation process of energy storage. Stakeholder interviews provided additional and helpful insights to the literature review. The stakeholders framed alternative potential future developments that could influence the market success and need for energy storage until 2050. Most important factors named where policy measures, new market models and decentralization of the energy system. As in literature there is a big uncertainty among experts about the right storage technology and if energy storage is in general the best option among other measures as grid reinforcement, flexible demand and flexible power plants. It remains impossible to provide suggestions regarding the development of single storage technologies.

Keywords: Electricity system; energy storage; technology assessment

JEL codes: O33, Q42, Q55

Resumo

A Alemanha tem metas ambiciosas para produzir 35% da energia necessária a partir de energias renováveis baseado-se principalmente em energia eólica e solar até 2020 e mais de 80% em 2050 no âmbito do chamado "Energiewende". O armazenamento de energia é visto como uma opção potencial para garantir a integração segura do sistema de fontes de energias renováveis (FER) para alcançar estes objetivos. Há um alto grau de incerteza e o discurso público dela resultante sobre a procura futura, e sobre o tipo mais adequado de tecnologia de armazenamento, impulsionam o desenvolvimento destas tecnologias. Uma revisão da literatura de 9 estudos e 10 entrevistas com especialistas foram realizadas em linha com um exercício de prospetiva para resolver estas incertezas. As estimativas de estudos revistos são modelos baseados numa perspetiva de mercado sobre a procura de armazenamento de energia. A maior parte dos cenários baseados em modelos tem lógicas de construção de cima para baixo, onde os processos em níveis mais baixos (tecnologia, esfera micro-económico) são determinados pelas macro-dinâmicas dominantes. Diferentes tecnologias são consideradas apenas parcialmente ou de forma agregada. Os estudos revistos mostraram que há um alto potencial de armazenamento em cada escala de tempo a partir do ano de 2030 a 2040. Os potenciais analisados variam em função da difusão de FER e de taxas de excesso de premissas entre 0 e 44 GW. Os estudos integram visões partilhadas sobre a evolução do sistema e análises formais e fornecem informações importantes e valiosas sobre possíveis implicações futuras. Mas, elas representam apenas parcialmente, devido a razões práticas e benefícios mais amplos, as opiniões das partes interessadas e mudanças contínuas. Representam também as descontinuidades no processo de inovação tecnológica do armazenamento de energia. As entrevistas com os interessados, forneceram informações adicionais e úteis à revisão da literatura. As partes interessadas nesta questão enquadraram desenvolvimentos futuros potenciais alternativos que poderiam influenciar o sucesso de mercado e a necessidade de armazenamento de energia até 2050. Os fatores mais importantes nomeados foram as medidas de política, os novos modelos de mercado e a descentralização do sistema de energia. Como na literatura há uma grande incerteza entre os especialistas sobre a melhor tecnologia de armazenamento e sobre se o armazenamento de energia é, em geral, a melhor opção entre outras medidas como reforço da rede, a procura flexível e centrais flexíveis de produção. É, no entanto, impossível fornecer sugestões sobre o desenvolvimento de tecnologias de armazenamento individuais.

Palavras-chave: Sistema de eletricidade; armazenamento de energia; avaliação de energia

Content

1 Introduction

Scarcity of fuels, changes in environmental policy and in society increased the interest in generating electric energy from renewable energy sources (RES) for a sustainable energy supply in the future [1]. This is also the case for Germany which has ambitious targets to produce 35 % of the needed electricity from RES by 2020 and over 80 % by 2050 within the so called “Energiewende” (energy transition) [2]. The main problem of RES as solar and wind energy, which represent a main pillar of this transition, is that they cannot supply constant power output. This can lead to temporary capacity problems regarding the high amount of fluctuating energy sources resulting inter alia in an increased demand of backup technologies as energy storage, demand side response and other technologies to assure electricity system safety [3]. Especially energy storage is an option that is highly discussed in the public. Electric Energy Storage is a process for converting electrical energy into a form that can be stored and later be converted back to electrical energy when needed [4]. It represents an enabling technology which improves the remaining electricity system, consistent of RES, grid infrastructure, residential power generation, power plants and regulation. Vice versa it is dependent on other energy system developments (markets development, RES-share, policies etc.) as well dynamics and do not represent a separately identifiable dominant system [5]. The future demand on energy storage technologies is thus characterized by a high magnitude of uncertainties. This has motivated the creation of numerous variations of renewable energy source and storage penetration scenarios as [6], [7], [8], [9]. This makes it difficult to draw a robust picture of the demand scenarios for this technology within the German Energiewende until 2050.

The aim of this work is to systematically analyse which developments and options for action are available for energy storage nowadays and to determine to what future outcomes this developments can lead. This is realized by the use and combination of different foresight methods, namely a literature review and semi-structured interviews.

2 Methodology: Used Foresight methods

Foresight approaches are a discussion object among academic researchers, industrialists, consultants, policy-makers and others. There are around 5.000 academic articles available in google scholar, while google registers over 90,000 hits. Foresight represents an explicit recognition that choices nowadays create the future and that there is little point in making deterministic predictions in spheres where social and political processes exercise major influences [10]. Coates [11] offers an early definition of foresight as follows:

"*..a process by which one comes to a fuller understanding of the forces shaping the long-term future which should be taken into account in policy formulation, planning and decision-making..*"

The discussions about foresight in academia are centered about processes, generations, challenges, classifications and various types of practices and methods. There is a large knowledgebase of frameworks, methods and experiences based on the use of wide spread of examples [12] [13]. A set of some typical methods used for foresight is given in table 1. It is important to mention here that foresight should not be seen as a purely set of methods. It is rather a process with the aim of better understanding of possible developments and the forces that shape them [10].

Table 1: Overview of Foresight methods

Qualitative	Quantitative	Semi-quantitative
Methods providing meaning to event and perceptions. Such interpretations tend to be based on subjectivity or creativity often difficult to corroborate (e.g. brainstorming, interviews)	Methods measuring variables and apply statistical analyses, using or generating (hopefully) reliable and valid data (e.g. economic indicators)	Methods which apply mathematical principles to quantify subjectivity, rational judgements and viewpoints of experts and commentators (i.e. weighting opinions)
1. Backcasting 2. Brainstorming 3. Citizens panels 4. Conferences/Workshops 5. Essays/Scenario writing 6. Expert panels 7. Interviews 8. Literature review 9. Morphological analysis 10. Scenarios/scenario WS 11. Surveys 12. Others (SWOT, etc.)	13. Benchmarking 14. Indicators 15. Bibliometrics 16. Modelling 17. Patent analysis 18. Trend extrapolation 19. Impact analysis	20. Cross-impact analysis 21. Delphi 22. Multi-criteria analysis 23. Polling 24. Quantitative scenarios 25. Roadmapping 26. Stakeholder analysis

Table based on based on Popper [12]

The methods within foresight are often selected by a multi-factor process which is dominated by intuition, insight, impulsiveness and sometimes irresponsibility and inexperience of practitioners and organizers. Additionally the choice of a method is also a question of domain, R&D Context, territorial scale, time horizon, sponsorship and target group [13]. For this work literature review and interviews are seen as adequate methods to carry out a foresight analyses on energy storage technologies in frame of the German Energy turn over.

3 Literature review about future energy scenarios and storage

The literature review is based on re-known studies about energy storage in Germany conducted in frame of [14], [15]. In total 9 large studies have been reviewed and compared. Aim of the review was to draw a picture of future energy storage demand until 2050. Thus main variables, scenarios and model structures were briefly analyzed and summarized, to dilute the resulting demand on energy storage technologies in Germany and to identify the main influence parameters that steer their development.

The named sources range from 2010 to 2015 and are available for the public. The studies are in all cases renowned sources from private and research institutions in Germany as e.g. the Fraunhofer institute. A brief overview of the 9 studies is given in table 2.

Table 2: Overview about reviewed literature in the field of energy storage within the German Energy turn-over

Authors	Title	Year	Aim of the study
M. Sterner et. Al	*Energiespeicher - Bedarf, Technologien, Integration*	2014	Overview about energy storage technologies and related scenarios from literature
UBA / DLR	Langfristszenarien und Strategien für den Ausbau der Erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global	2011	Provides scenarios for renewable energy capacity development. illustrate the associated structural changes as well as demand for flexibility options
Agora Energiewende	Stromspeicher in der Energiewende - Untersuchung zum Bedarf an neuen Stromspeichern in Deutschland für den Erzeugungsausgleich, Systemdienst- leistungen und im Verteilnetz21	2014	Provide overview of potential energy storage demand scenarios, problems and potentials as well as techno-economic properties of storage technologies
SRU	*Wege zur 100% erneuerbaren Stromversorgung: Sondergutachten*	2011	Illustrate the structural changes for a 100 % RES based energy systems with related storage demand
F. Genoese	Modellgestützte Bedarfs- und Wirtschaftlichkeitsanalyse von Energiespeichern zur Integration erneuerbarer Energien in Deutschland	2013	Analyze the techno-economic impacts of fluctuating electricity generation on the German power grid until 2030 and the resulting demand of energy storage technologies
W.-P. Schill et al	Stromspeicher: eine wichtige Option für die Energiewende	2015	Analyze long term need for energy storage technologies and competition to other technologies
W.P. Schill	Integration von Wind- und Solarenergie: Flexibles Stromsystem verringert Überschüsse	2013	Analyze potential surpluses of renewable energy generation in relation to demand and find options to use these
Auer and J. Keil	Moderne Stromspeicher Unverzichtbare Bausteine der Energiewende	2012	Analysis of impact of renewable energy generation on grid and resulting market potential for energy storage technologies
Pape et al.	Energieziel 2050: 100% Strom aus erneuerbaren Quellen	2010	Analyse measures to achieve a greenhouse gas emission reduction of 80 to 95 % in Germany in a economic viable way

Table based on [5], [7], [8], [9], [16], [17], [18], [19], [20]

All mentioned studies don´t have the aim of predicting the future, they rather create a context in which potential development paths can be visualised 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.

3.1 Energy Storage Technology overview

Energy storage technologies can generally be divided into; 1) mechanical: Pumped Hydro-Electric (PHS), Compressed Air Energy Systems (CAES), Flywheels; 2) electrical; Super Conducting Magnet Energy Storage; 3) thermal: heat storage in cavern or rocks, molten salt; 4) electro-chemical systems: battery systems and hydrogen [21] [22]. Storage technologies make it possible to increase system reliability and flexibility by decoupling demand and supply of electricity in a time dimension. It has to be mentioned that energy storage is seen as one potential balancing option among other technical alternatives as combined cycle gas turbines (CCGT), grid reinforcement measures (new AC or DC transmission lines), demand side management, Power to X (e.g. to produce natural gas or hydrogen) or generation management of renewables within the German "Energiewende". Table 3 gives a brief overview of the main characteristics of different storage technologies.

All storage technologies can be categorized in certain 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 [23]. These application possibilities have different cost and technologic tolerances, which highly affect the applicability of different storage options.

Table 3: Overview of 25% quartiles, median and 75% quartiles of different balancing options

Technology	Efficiency	Gravimetric energy density	Gravimetric power density	Cycles	Life time	Investment cost	Comment
	[%]	[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	Cost is dependent on application
Li-Ion (various)[1]	81-91-98	84-115-145	253-640-1,300	0.73-2-8	7.5-15-20	453-745-1,227	Most common used battery type
Lead Acid[2]	63-76-90	23-33-37	3-27-53	0.3-1.6-1.8	10-18-20	179-230-320	Mostly used for ups
High temperature (various)[3]	75-86-90	120-148-158	113-160-196	2.8-3.6-5.9	10-14-17.5	172-295-440	NaS and NaNiCl, the latter is seen as safer and better
Ni-based[4]	60-81-85	58-57-46	140-186-477	0.8-1.6-2.5	7.1-12-13	290-1,200-2,300	NiCd and NiMH old generation batteries
Pumped hydro storage	65-75-85		0.5-1-1.5	10-16-50	30-40-60	46-500	Dependent on geology
CAES	54-70-88	3.8-5-6	-	6-12-20	20-35-40	3-40-300	Dependent on geology
CCGT	54-60-63	-	-	-	20-30-40	680-900 [€/kW]	Alternative to storage
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	Very expensive, only viable for short term applications

Table based on Stenzel et al. [24] and Baumann et al. [25]

[1] Summary of LFP, NCA, NMC, LTO, LMC without peripheries (inverter, balance of plant etc.)
[2] Summary of VRLA and Flooded Lead acid batteries (inverter, balance of plant etc.)
[3] Summary on NaS and NaNiCl batteries (inverter, balance of plant etc.)
[4] Summary of NiCd and NiMH (inverter, balance of plant etc.)

3.2 Scenarios of Renewables and energy storage systems

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 [2] which is flanked by the German federal government. Fluctuations of a high amount of RES including extreme ramps, excess energy and forecast errors can cause blackouts when there is no sufficient balancing option as energy storage is available. This 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 [3]. The future development of renewables is thus key to the future demand on energy storage technologies.

One of the most cited and used scenarios for RES penetration within the German Energiewende are based on the German Aerospace Center (Deutsches Luft- und Raumfahrtzentrum - DLR) [7]. The scenarios have been built in orientation to the goals of the German federal government and illustrate the associated structural changes. They also highlight different paths of the developments in the transport sector. An overview of all considered scenarios with a detailed insight to scenario B is given in figure 1. In total three main scenarios 2011 A[5]; B[6] and C[7] were taken into account. These main scenarios were supplemented by two additional scenarios 2011 A´[8] and scenario 2011 THG95[9] [7].

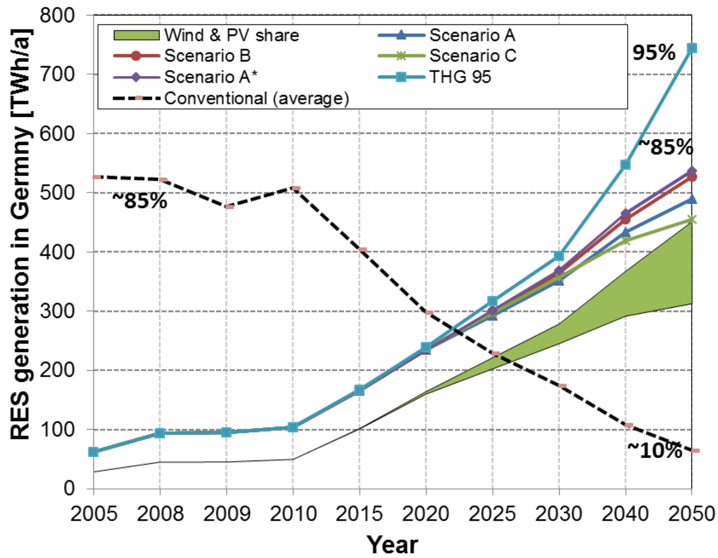

Figure 1: Potential RES generation for various scenarios until 2050

Source: own figure; summary of database provided by DLR [7]

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[5] 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

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

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

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

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

The main differences between main scenarios are variations in assumptions regarding the transport sector. 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 Wind power (Wind) contribute of 50% to 75 % to total RES generation [26] in all scenarios (bandwidth of min and max penetration scenarios is given in green in Figure 1). The share of low carbon technologies in the electricity mix is estimated to increase from around 45% nowadays and nearly 100% in 2050 [22]. In contrary, conventional generation capacities including coal, nuclear and gas power plants will be drastically reduced from around 85% down to 10 % in 2050.

3.3 The need for scenario building for energy storage demand

The need for storage is highly related to other developments in the energy system on a generation, grid, demand and market level. There is thus a high amount of large and complex 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 [16], [8], [18]. These assessments often don´t allow a differentiated view on different storage technology types. Instead generic technologies for power or energy applications are used due to practical reasons. Table 3 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.

Table 4: Summary of system development that influence the need for energy storage technologies

Demand for storage	**Generation level**	**Distribution / grid level**	**Demand side**	**Markets**
Increased +	1) Development of RES 2) Remaining share of must run capacities 3) Forecast errors of RES 4) Share of inflexible power generation[10]	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 fore-cast 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 demand side management in power markets 3) Decrease of demand	1) Low wholesale energy prices 2) Low consumer and electricity prices 3) Low CO_2 costs

Sources: Agora Energiewende [8], Genoese **[16]**, Adamek et al. **[18]**, Schill et al. **[17]**, Gerhardt et al. **[28]**, Schill **[29]**

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

There is in general a difference between market and system based need for storage. The latter refersto 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. Such situations arise when contracted energy cannot be physically delivered due to grid restrictions or in cases of grid errors or breakdown of large generation units. 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 [23]. This situation can lead electricity wholesale markets to tumble and spot market prices may spike by falling below 0 €/MWh or in contrary over 100 €/MWh. Both forms of storage demand are dependent of the share of RES in the energy system and the estimated degree of generated excess electricity (non-usable share of electricity due to low demand). Storage technologies are seen as a possibility to store excess energy and feed it back into the grid in peak times. Thus a set of studies was compared as depicted in figure 2 to unveil potential RES excess impact scenarios for the German energy system until 2050.

Each mark represents a single scenario for a specific year. It can be observed in figure 2 that most scenarios draw a pretty common picture until the year 2035. Starting form 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 [16], DB research 2013 [19] and Fraunhofer ESP 2011 [30] tend to have relatively moderate and comparable impact scenarios whilst SRU 2011 [9], Ökoinstitut 2014 [31] and UBA 100% [32] are considered with higher RES impacts of up to 100 TWh per year [11]. Nevertheless, 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). The assumptions about the amount excess energy through RES often serve as a base for simulations to identify the potential need for balancing options.

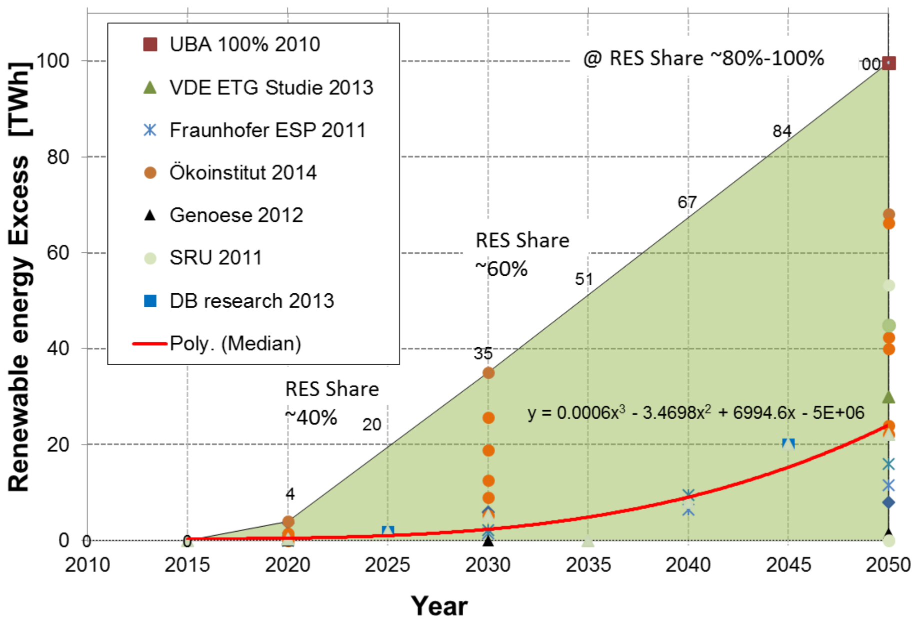

Figure 2: Various scenarios for the development of RES in Germany, Source: own figure; summary literature review inspired by [33]

[11] This would represent about 18 % of the German energy demand nowadays

Most studies in the field identify at least three application areas to determine the need for energy storage. These are namely: a) power applications and b) energy applications and c) for long term storage over several days. Area (B) involves the discharge over hourly periods (several cycles per day) with relatively long charging periods to use the stored energy for example to decouple the timing of generation and consumption of electricity [34]. The first category (A) has short periods of discharge (milliseconds to minutes up to one hour), short recharging periods and involves many cycles a day [35] to ensure continuity, quality and proper frequency of the delivered electric power in real time [34]. Finally (C) includes the use of energy over a long period to overcome e.g. long phases of without wind or solar irradiation. The following two sections will give an overview of the potential demand of this three forms of storage.

3.4 Scenarios for short to mid-term storage demand

The market need for energy storage in this studies is mainly defined on the bases of arbitrage businesses on a transmission grid level (exceptions are Agora [36] and Grünewald [16][12]). 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 [8], [18] and [29] where the grid is modelled as a copper plate (see VDE –ETG [18], BMU Langfristszenarien 2012 [7], SRU 2011 [9] and Genoese [5]). The need for storage on a distribution or mid-voltage grid level is thus often expulsed as is difficult to make robust prognoses in this field [37]. Redispatch[13] and frequency regulation are thus consequently also often excluded and only discussed qualitatively.

Figure 3 illustrates different energy storage diffusion scenarios based on wholesale market needs for short (figure A) and mid-term storage (figure B). The red line indicates a 2nd degree polynomial regression of indicated median values obtained from all given sources to draw a most probable scenario for storage demand over time.

[12] Considers tertiary reserves

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

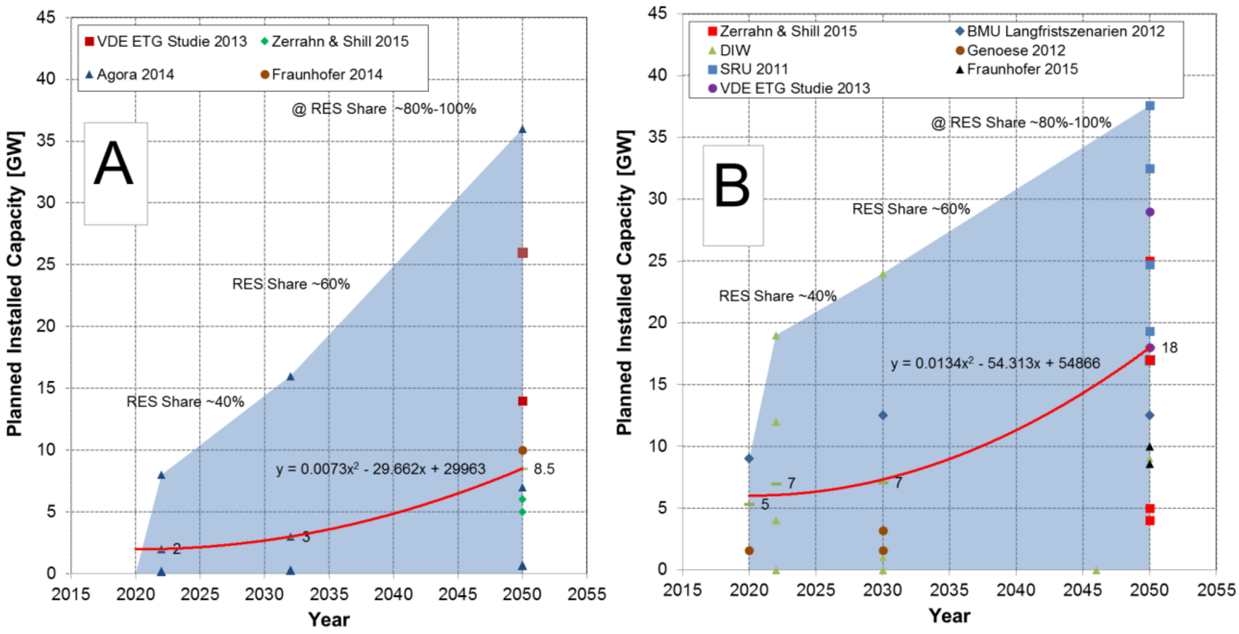

Figure 3: A) Potential demand of short term storage capacities (<4 h per day) until 2050, B) potential demand for mid-term storage capacities until 2050 (<10 h per day), Source: own figure; based on [5], [7], [8], [9], [16], [17], [18]

The most valuable scenario E of the VDE – ETG Taskforce for Energy storage [18] estimates 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 [8] are very broad. Both [18] and [8] 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 economical viable. Scenarios between Zerrahn and Shill 2015 [17] are more moderate with low variations as the amount of excess energy is not considered as that high. All scenarios have in common that short term storage take-off is considered to be around 2035 when a RES share of 60% is achieved (see red line in figure 3 A). This can be explained through the extrusion of residual load power plants through RES. Only low capacities of an average of 2 to 3 GW are required before that time.

The need for mid-term storage (8-10 h) demand is higher in relation to short term storage. The VDE – ETG Taskforce [18], Genoese [16], calculated an average need of 18 GW and 7 TWh storage capacity [26]. Droste-Franke [38] (not included in the graph) reports that economic viable storage capacities in 2040+ could be about 15 GW. Scenarios within SRU 2011 [9] consider that electricity supply is covered by 100 % through RES in 2050[14]. The need for storage over time is comparable to short term storage needs, with a take-off at a share of 60 % share of RES. The higher amount of required midterm storage can be explained through longer deviation in RES production that has to be mitigated. However, it is clear that energy storage will play an important role in the future energy system.

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[14] 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)

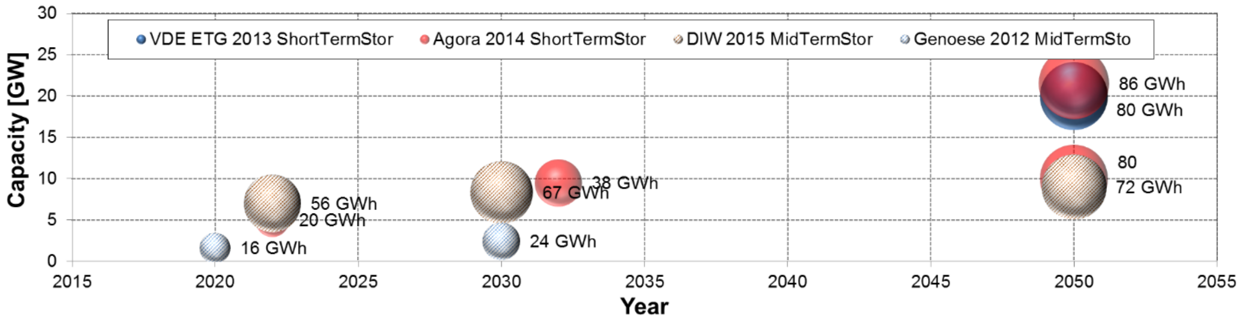

Figure 4: Potential energy storage demand (4 to 10 h per day) until 2050 including power and capacity, Source: own figure based on, [8], [16], [17], [18]

3.5 Scenarios for long-term storage demand

The need for long term storage technologies with storage times of over 700 hours or multiple weeks per year [8], [17], [29] is seen as very high in case of high RES shares. Figure 5 A gives an overview of the potential demand for long term storage from 2020 to 2050.

Schill et al [17] states that only small long term storage capacities are required in a 100 % RES generation case, up to 30 GW in a special scenario without biomass power plants. DIW [29] calculated that the demand of long term storage is highly dependent on the overall flexibility of the power system. Depending on the degree of the flexibility long term storage demand would vary between 7 to 40 GW (non-flexible to very flexible system). The UBA 100 % study considers hydrogen and synthetic methane as long term storage option with the ability to compensate 99 % of RES surpluses. The potentials were assumed on basis on available caverns in Germany for hydrogen storage. UBA Langfristszenarien [7] uses comparable assumptions. Agora calculated storage demand on base on a 90 % to 60 % RES scenario with 16 GW and 8 GW respectively with 720 hours of storage capacity. An overview of required average capacities for long-term storage in relation to mid- to short term storage is given in figure 5 B. It can be seen that long term storage capacities are significantly higher in terms of capacity then the other ones.

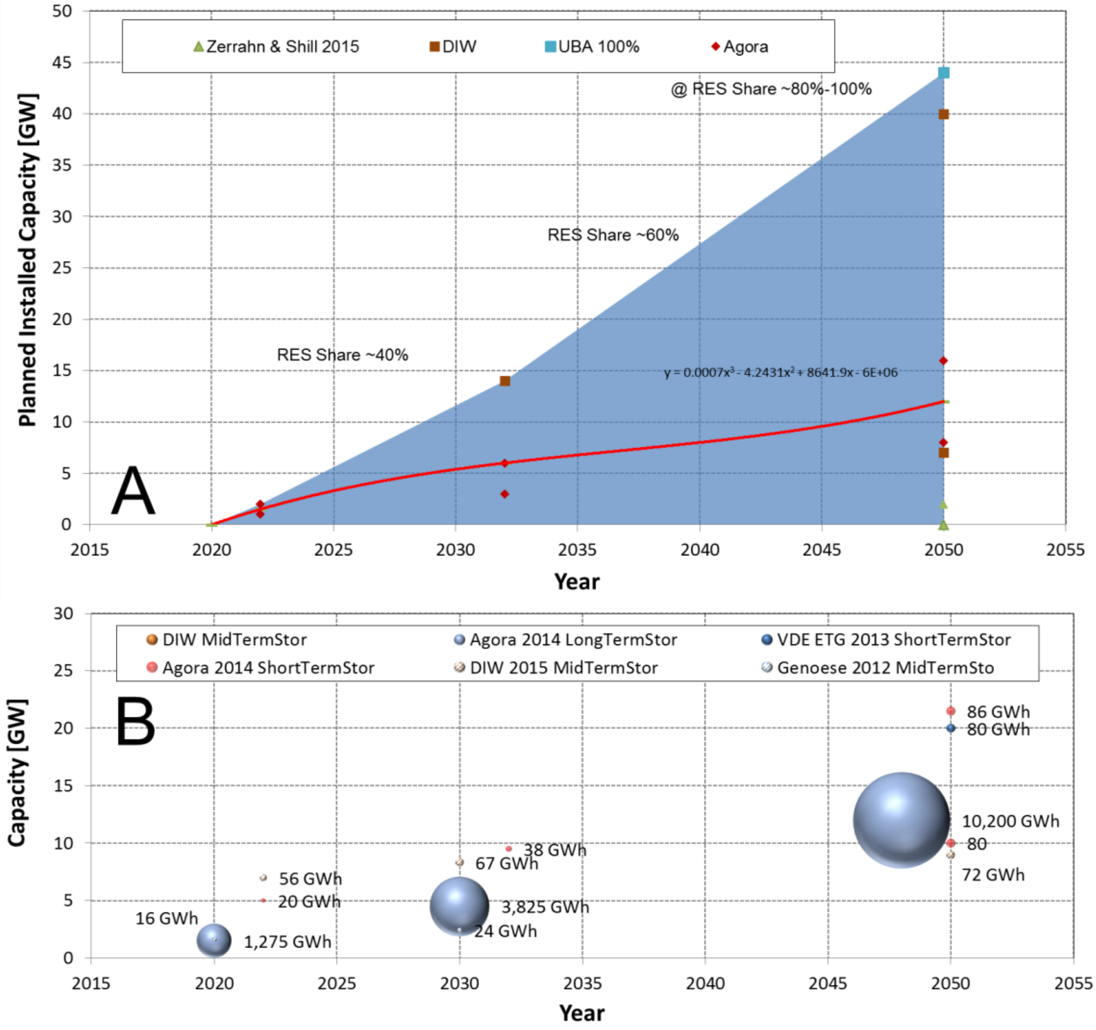

Figure 5: Potential demand of installed long-term storage capacities (>days h per day) until 2050; B) Potential energy storage demand (4 to 10 h per day) until 2050 including power and capacity, Source: own figure Source: own based on [5], [7], [8], [16], [17], [18]

3.6 Results of the Literature review

The need for balancing options is highly dependent on the further development of RES capacities in Germany. It has been shown that Wind and PV are the most important energy source in the future with contributions of over 70 % on overall electricity generation in 2050. The system integration of these technologies is challenging due to their intermittent nature and cost structure. Transmission grid operators will face stronger power ramps and higher amounts of forecast errors in face of a decreasing number of flexible power plants. At the same time market conditions are highly affected by RES. There is thus a strong consensus within literature that energy storage technologies on different time scales and sizes will be required in the future. The take-off of these technologies is considered to be after 2035, before this time only low capacities are required (up to 3 GW). Estimations for 2050 show a broad picture of required balancing capacities of about 0 to 35 GW for short term (up to 4 hours) and 0 to 38 GW for mid-term (over 8 hours) storage out of a market perspective. Estimation in the field of long term storage show even higher variations of 0 up to 44 GW until 2050. It has been shown that required capacity for long time horizons can be up to 10,2 TWh.

The presented studies are heavily dependent on data (e.g. quantitative inputs as energy, raw materials, ancillary, physical or required operation conditions, life time, maintenance, cost etc.) and very time complex. The availability of data and the possibility of quantifying them are two critical aspects. Most assessments start with extrapolations of available data into the future by the development of scenarios (e.g. combination of learning curves, economies of scale, linear upscaling with data from mature comparable systems etc.). Such scenarios have to be developed carefully and have to deal with high uncertainty of data and of their often poor availability. Additionally the complexity and dependency on tangible factors and uncertainty a system analyst's imagination might cause technology to proceed along a certain trajectory (in the way a rocket follows a trajectory as soon as it has been launched), based on a dominant socio-technical regime (market structures, technology etc.) serving as a base for modelling and result presentation. An example here fore might be notions about what the "market" (end users) wants and how new technology might be used (and thus modelled within its use phase) [15]. But, market demand does not articulate itself in a unambiguous and quantitative way [39]. The articulation of extrapolations and "dynamics as usual" is thus problematic as markets evolve.

[15] All the analyzed energy market studies can be named here as there are based on the merit order model, including the typical way of margin cost calculation nowadays

4 Visions about the power system and energy storage

The motivation to conduct interviews in this research was to obtain a deeper insight into stakeholder´s expectations and visions they have for the future use on energy storage systems beyond those communicated in the reviewed studies. Semi-structured interviews are explored to provide sufficient structure as well as flexibility to tackle this task.

4.1 Stakeholder involvement: Semi-structured interviews

The interviews were conducted in frame of a pre-test phase of a online survey in the frame of a PhD project on energy storage [14]. The named survey was initially distributed with individual mails to 22 experts from the area of energy storage and power systems. The first contact briefly introduced the topic of the survey and potential interview. The mail stressed that the aim is to get a critical feedback on the survey as well as to gather general expectations about energy storage. Candidates were also asked if they are willing to participate on follow-up interviews. In total 13 external experts responded providing various comments and thoughts on the topic. From these 10 candidates were willing to participate in an interview. An overview of the participants and way of interview is given in table 5.

Table 5: Overview of interview actors

Stakeholder index	Company/Organization	Profession	Comment
P 1 RE	Private Research Institute	Head of Energy department	Via telephone, ~40 minutes, notes
P 2 U	Utility company	Head of department	Via telephone, ~50 minutes, notes
P 3 RES	RES Systemintegrator	Senior operation services	Via telephone, ~115 minutes, notes
P4 U	Utility company	Senior consultant	Via telephone, ~40 minutes, notes
P 5 U	Utility company	Head for energy storage project development	Via telephone, ~50 minutes, notes
P 6 Reg.	Regulation agency	Expert of the department of RES and energy efficiency	Via telephone, ~90 minutes, notes
P 7 Auto	Automotive	Vice head of project management	Via telephone, ~80 minutes, notes
P 8 ES	Energy storage business	Project management	Via telephone, ~90 minutes, notes
P 9 Ac	R&D University	Principal investigator energy storage research	Personal, ~80 minutes, notes
P10ConPol	Energy Policy consulting	Consultant & Professor @ Univ.	Via Telephone ~20 min, notes

The interviews were conducted mostly via telephone due to the large physical distance of the candidates. Only one personal interview was conducted with a participant working in the same city. Each interview had duration between 30 to 100 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 arranged that the material will be used in an anonymized form without direct quotation.

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 transcript directly after the inquiry and included only the most important points of the interviews. This phase has led to further alterations of the survey and offered valuable additional qualitative information about the questions raised.

4.2 Stakeholder expectations on the future energy system

Most of the participants believe in a success of the energy turn over [P5U, P3RES, P9AC, P1RE]. Though there are doubts about the magnitude of RES shares and concerns about missing strategies to achieve them on a policy and regulation level. The issue of regulation was often connected to the German Renewable Energy Act (Gesetz zur Förderung erneuerbarer Energien –EEG). The EEG is considered as a key in the transition, in the sense that it should attribute a higher degree of personal responsibility to RES asset owners. Especially regulation for residential storage[16] and the obligation of (more) direct marketing of RES[17] [P5U] were named as crucial aspects.

Participant P10ConPol stated that the market impacts of RES are well understood. Most studies in the last 5 years go in line about the effects of RES on wholesale markets. This can be validated through the conducted literature review which showed that a lot of studies are available. In this context some actors claimed that available energy models don´t account changes in market design and wider technology use and may systematically underestimate storage technologies. Stakeholder P5U claimed that market models have a short validity due to the fact that it is unclear if market clearing prices and margin costs will be calculated the same way in 2030. Interview results have led to the impression that participants agree that RES impacts on system safety are to a certain degree systematically underestimated. Problems named in this context where high dispatch costs and grid congestions. This is on the one hand based on the logics of applied energy models that use a "copper plate" grid approach and don´t consider this effects [P10ConPol]. Furthermore short term fluctuations are also not properly considered as mostly hourly time steps are used in most modeling approaches [P5U]. On the other hand RES growth was underestimated in the last 5 years. Transmission grid operators did not anticipate the amount of grid congestions and dispatch costs related to the system integration of wind and PV [P10ConPol].

Literature points out that future energy systems will be highly decentralized [5], [8] offering new potentials for energy storage, especially battery systems [41], [8]. The next question thus aimed to find out of how strongly actors agree that the energy system will be strongly decentralized. There was a strong consensus in favor of this statement among the interviewees P9Ac, P3RES, P4U. Interviewee P5U expressed his approval as follows:

… the future system will become more small sized […] with a higher degree of individual responsibility[18] […] 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.."

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[16] See e.g. §§ 118 Abs.6 and 60 Abs. of the 3 EEG – regulations for residential storage
[17] This is already obligatory for all new RES generation units >500 kW starting from January 1st 2016 [40]
[18] In the context of local energy consumption and regulation

It has to be mentioned that this change is seen until 2050. Some participants believed that there will be a balance of central multi MW and small multi kW power plants until the 2030ies. Large investments in the field of GW units are told to strongly decrease in the future [P6Reg] and [P10ConPol].

4.3 Expectations on future energy storage diffusion

The interviews showed that all participants agree that there will be to a certain degree a need for energy storage in the future German energy grid. The validity of available studies estimating the need for storage was also addressed in the interviews in terms of made market assumptions [P5U] and considered business models [P2U] and [P7Auto]. Candidates claimed that there already exist several technologies, but that there is no business case available making it hard to make any robust estimations. The value of energy storage cannot be directly allocated to one actor as there are several beneficiaries of services provided (e.g. energy storage unit in combination with a wind energy direct marketing leading to transmission and Distribution upgrade deferral (T &D upgrade)). This is problematic as the investment into storage is conducted by one party but value streams affect multiple actors and remain unclear. Thus storage services provided have to be accordingly rewarded which is not the case nowadays [P7Auto]. The integration of these values should generate a more efficient system approach. Especially new system concepts as virtual power plants offer completely new business possibilities for scalable battery storage [P5U]. The problem is that the composition of these concepts itself is considered to be in their infancy and remain blurry.

There was no consensus about the amount or kind of balancing options needed until 2050 as expressed through [P1RE, P2U, P4U, P8ES]. They also stressed that balancing does not have to be covered by energy storage as there are several other options available [P1RE, P2U, P4U]. Stakeholder P5U did not agree to the time frame after 2035 and thinks that flexibilization options will be required earlier due to system safety issues starting at a RES share around 40 %[19]. Candidates as P4U and P1RE agreed that it is in general difficult to make reliable predictions for single technologies. 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"*

P4U added that the specific technology is not of interest out of energy economic perspective. The interest is more nested in the bigger context with a general view on storage and not on single technologies. The interviews showed that there is a lot discussion within the community regarding the need for storage on all levels [P1RE, P2U, P4U, P5U, P7Auto, P8ES]. It was also pointed out that energy storage is only one of four possible balancing technologies 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. The latter is seen as too expensive in relation to the other options [P8ES]

[19] This would refer to the year 2025 regarding the analysed studies in chapter XX

[P10ConPol]. One stakeholder also expressed concerns about the strong willingness of policy to support energy storage projects due to the fact that they might “*bet on the wrong horse*” [P10ConPol].

In general all 4 named balancing options are seen as important to a certain degree. Some measures are considered as more intermediate solutions as transmission grid extension and flexible power plants [P8ES]. A major problem regarding demand side response (DSM) are problems regarding acceptance. The issue of acceptance is reinforced by the low acceptance of the required smart meters for DSM and related costs nowadays. This was especially pointed out for industry regarding the fear of losing to a certain degree control over their production [P7Auto]. There is only seen a small potential for DSM in the end-user markets due to missing business cases and small profit margins [P6RES], [P5U]. One exception was mentioned by the use of wall boxes to conduct DSM with electric vehicles [P7Auto].

The potential for large, 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 [P10ConPol]. Existing PHS are already operating at the brink of being economic viable [P8ES]. The technology may serve as a backbone for system stability in combination with decentralized storage options in the future [P10ConPol]. Other technologies named in the context of centralized energy storage were power to gas and hydrogen.

Grid extension is perceived as elemental for the success of the Energiewende. Despite the need for it most candidates argued that this option is highly unpopular within population [P3RES], [P7Auto], [P5U]. This was stressed in almost all interviews. The option of building new flexible power plants (e.g. gas-turbine) is seen as unproblematic regarding local acceptance [P6Reg]. This is surprising as they also represent a centralized technology with a certain impact on landscape and air quality. It was however stated that the technology is well known for its safety and that is relatively cheap in relation to other options.

Modular technologies as battery storage are seen as important for certain applications especially for short-term applications as frequency regulation. Most interviewees doubted that battery technology can compete with any of the given alternatives due to their bad comparable economic performance. Thus participants perceive them as not that relevant for the years to come [P3RES], [P8RES] and [P10ConPol].

The value of battery storage cannot be directly allocated to one actor as there are several beneficiaries of services provided (e.g. battery storage in combination with a wind energy direct marketing leading to transmission and Distribution upgrade deferral (T&D upgrade)). This is problematic as the investment into storage is conducted by one party but value streams affect multiple actors and remain unclear. Thus storage services provided have to be accordingly rewarded which is not the case nowadays [P7Auto]. The integration of these values should generate a more efficient system approach. Especially new system concepts as virtual power plants offer completely new business possibilities for scalable battery storage [P5U]. The problem is that the composition of these concepts itself is considered to be in their infancy and remain blurry.

4.4 Results of the semi-structured interviews

Stakeholders believe in the success of the Energiewende, but are not in line of how to get there. The need of balancing technologies is highly discussed, not in the sense if they are required but when and in which amount. It can be diluted from the inquiry that changes in the architecture of the energy system towards a more decentralized system and lower large scale investment might represent a big opportunity for storage in the mid- (2035) to long-term (2050). There is a high degree of consensus among participants that RES impacts are under-estimated not on market level but on a system level are. Major issues in this context are missing regulations within the EEG, whole-sale market structure and the loss of an overarching strategy to achieve the *Energiewende*).

Energy storage is seen as one option among: 1) Grid reinforcement measures, 2) flexible demand, 3) flexible power plants and at the end of the line 4) electric energy storage in economic terms. Option 1 and 3 are seen as intermediate measures with a decreasing importance in the future. Flexibility measures as Demand Side management is seen highly critical due to acceptance and cost of smart meters. Most stakeholder don´t see a big potential for centralized large energy storage technologies. The survey attributes a high relevance to modular technologies as battery systems. Interviews have shown that they are seen as one of the most expensive technologies within the segment of energy storage technologies. It was concluded that no business case are available making it hard to make any robust estimations about single technologies.

5 Conclusion and discussion

The estimations of reviewed studies are based on techno-economic linear optimization models with the goal of minimizing overall system costs with a market based perspective on energy storage demand. Only few studies consider system based demand of storage on multiple voltage levels. Most model based scenarios are built on top down logics, where processes at lower levels (technology, micro-economic sphere) are determined by dominant macro dynamics (existing market mechanisms, business models). Different technologies are only considered partially or in an aggregated way. The reviewed studies showed that there can be a high potential storage on every time scale in general starting from the year 2030 to 2040. Analyzed potential in the studies vary depending on assumption between 0 to 44 GW.

The studies strongly integrate shared visions about system developments and formal analyses and provide important and valuable information about potential future implications. These approaches often only partially account, due to practical reasons, wider benefits (system safety, environmental and social impacts etc.), stakeholder opinions, sustainability conditions and continuous changes as well as discontinuities in the technological innovation process [36] [42]. Stakeholder interviews thus provided additional and helpful insights to the literature review. Stakeholders framed potential future scenarios that could influence the market success and need for energy storage until 2050. Most important factors named where policy measures and decentralization of the energy system.

There is a big uncertainty about the right storage technology and if energy storage is in general the best option among other measures as grid reinforcement, flexible demand and flexible power plants. In general it appears the expectations and visions of stakeholders regarding energy storage strongly correlate with the set of studies reviewed[20].

[20] This underpins that decisions, public debates and policies related to energy storage are often explicitly or implicitly based on these modeling grounded studies as [8], [18] and [16].

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