Expert Views on the Role of Energy Storage for the German Energiewende

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"Energy Storage Technology and Large-scale Integration of Renewable Energy"

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Abstract: As the German "Energiewende," or energy transformation, propels renewables in the power sector to increasing penetration rates, research over flexibility options for electric system reliability has come into focus. This study analyzes semi-structured interviews conducted to investigate expert views over the role of energy storage for variable renewable integration in Germany. Interviews were conducted with a range of respondents from government, industry, business, academia, and think-tanks. We find that storage fits in the "gap" where other flexibility measures are seen as limited, with the size of this gap varying among expert views. In the short-term (to 2020) experts expect traditional measures of flexibility, namely thermal power plants and strengthened domestic interconnection in Germany, to continue to play the primary role for renewable integration. Experts agreed that storage increases in importance over the long-term as more renewables come into the system. The most significant factor for how an expert viewed the role of storage was whether future electricity production would become increasingly decentralized or remain centralized; a decentralized outlook implied a more important role for storage. For storage technologies, the largest areas of agreement occurred over power to heat and power to gas, where power to heat was considered easily implemented but limited in its ability to integrate renewables, and power to gas highly rated for seasonal storage in the long-term. Experts recommended that regulation of storage in Germany be clarified.

Keywords: Energy Storage; Renewable Integration; Variable Renewables; Flexibility Options; Semi-structured Interviews; Germany

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1. Introduction and Background

The German "Energiewende," or energy transformation, is an ambitious national program that aims to fundamentally alter how Germany produces and consumes energy. In the electricity sector, targets have been set for the increased share of renewable sources - in 2020 at least 35% of gross electricity demand should come from renewables, 50% by 2030, 65% by 2040, and 80% by 2050 (BMWi and BMU, 2010). These targets will only be met when fluctuating renewable sources of energy – mainly wind and solar power – are utilized to a large extent in Germany.[2]

In order to ensure a reliable electrical system, demand and supply of electricity must balance at all times. In Europe, this is achieved by ensuring that the grid operates at 50 hertz, a measure of frequency. Reliance on fluctuating sources of energy in the electricity sector poses a range of challenges for the German power system (Schill, 2013a). In order to cope with these challenges, several flexibility options have been identified (BMU, 2012). Traditionally, conventional power (coal, natural gas, and nuclear power) have been relied upon for flexibility, both to add and reduce supply of electricity when demand decreases and increases. A grid where increasing amounts of energy production depends on the availability of wind and sun presents a potential paradigm shift for ensuring system reliability, which has traditionally primarily focused on fluctuations in demand rather than supply.

This issue has taken on growing importance throughout the literature, where quantitative and qualitative analyses further the understanding of flexibility options and possible demand and supply curves in systems with large amounts of variable renewable energy. A study conducted by BET (2013) on the subject models a German electricity system where 47% of electricity demand comes from renewable sources by 2020. In this scenario, the maximum residual demand (demand after subtracting renewable feed-in) is 75 Gigawatts (GW); the minimum residual demand is -25.7 GW, demonstrating hours where renewable energy production exceeds demand. The Sachverständigenrat für Umweltfragen (SRU), a scientific advisory to politicians over environmental issues in Germany, conduct their own calculations and provide an overview and analysis of many of the key studies from German institutions that describe 100% renewable scenarios and related flexibility options (SRU, 2011). Schill (2013b) also models the German system under various scenarios, showing the interaction of flexible thermal plants, curtailment, and storage. More qualitative approaches exploring the flexibility concept include the International Energy Agency (IEA, 2011), which provides an approach to flexibility for policymakers and an exploration of the system challenges posed by variable renewables. The study also poses estimates for flexibility

[2] For instance, DLR et al. (2012, pp. 11, 309) in their scenario A for 2050 expect the majority (about 76%) of renewable energy in the electricity sector in Germany to come from wind and solar power, not including imports. This represents 55% of the total gross electricity production for this scenario.

requirements by region. Ruester et al. (2012) discuss the importance of flexibility options in the European system and the potential for storage to play a greater role, as well as regulatory and market uncertainties facing storage technology in Europe.

These studies provide a fundamental understanding of the concept of flexibility as well as calculations to quantify flexibility requirements for the integration of variable renewables. Such calculations require a large amount of assumptions which may be opaque and difficult to parse. In contrast to this approach our study utilizes semi-structured interviews to *expose* a range of plausible assumptions among experts, thereby allowing for greater transparency of the current discussion. Horton et al. (2004) explore the benefits afforded semi-structured interviews, whereby respondents have the freedom to explain and clarify answers through follow-up questions – this was found to be critical in this study. Talja (1999) looks at how such interviews ought to be assessed, emphasizing that the interviewer take into account the variability of respondent answers and interpretations of posed questions. In this study the context, criteria, and variability of responses are a central aspect of our results.

Examples of the use of semi-structured interviews in the energy sector abound in the literature, though largely do not to relate to the topic of flexibility measures. Schaefer et al. (2012) look at the possibility to introduce a feed-in tariff (FIT) for New Zealand by examining the views of high-level wind energy stakeholders and land-owning farmers. Interviews conducted at the national level in China examine perceived necessity and risks for carbon capture and storage (CCS) (Dapeng and Weiwei, 2009). In the U.S., Feldpausch-Parker et al. (2011) conduct semi-structured interviews with state-level energy stakeholders and analyze newspaper coverage in selected states to assess public discourse over CCS. Nooraei et al. (2013) utilize semi-structured interviews at an even more granular level to assess tenant issues at a "low carbon" apartment complex in the United Kingdom (UK). The study utilizes a Likert scale (ranking from 1 to 7) to aggregate tenant opinions on various design, quality, and comfort aspects in the apartment complex. Also in the UK, Rogers et al. (2008) examine public perception of locally driven renewable energy projects.

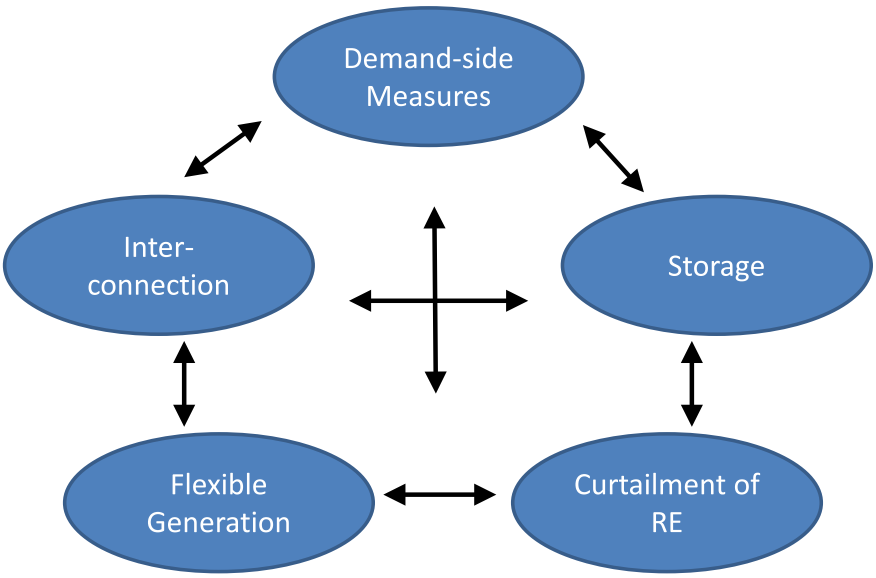
The study presented here utilizes semi-structured interviews to ask energy experts their views on flexibility, with a focus on the potential role of energy storage for integration of variable renewables in the future German power system. Our goal was to first assess what expert views on the role of storage and storage technologies for renewable integration in Germany *are,* then examine the background and assumptions as to *why* these views are held. We aim to unravel the current discourse and a range of assumptions over future storage implementation in Germany, which influences policy and regulatory efforts at a high level. Without a full understanding of these views and the range of opinions and assumptions that exist, sub-optimal or inefficient decisions may occur in the implementation of the Energiewende. The debate in Germany also informs interested stakeholders in other countries and regions.

Many of the questions in the questionnaire (see appendix for the full questionnaire) refer to specific aspects of the future use of storage in the German system. Those examined in close detail here are question 1.1, which places storage in the context of other grid flexibility measures, question 3.2, which asks experts to share views on specific storage technologies, and section 4, which asked experts about storage in the context of policy, market, and regulatory frameworks in Germany. First, background information for grid stability measures and energy storage technologies are presented, followed by the methodology of this study which includes an overview of the questionnaire presented to participants. Expert views on flexibility measures, storage technologies, and regulatory and institutional aspects for storage in Germany are then explored, and finally an overall summary and conclusions are presented.

1.1 Overview of Flexibility Options for Renewable Integration

As discussed, increasing amounts of fluctuating renewable energy places additional emphasis on measures to balance demand and supply of electricity. In such a system, every avenue of flexibility ought to be considered to determine the best option(s) from an economic and social standpoint. Denholm and Hand (2011) discuss flexibility options in Texas and VDE (2012a) the case of Germany. See also BMU (2012), BET (2013), and Schill (2013a). These measures interact with each other to a large extent, demonstrated in Figure 1, based on Fuchs et al. (2012).[3]

Figure 1. Flexibility Options in the Electricity Sector



The flexibility options seen above interact as both substitutes and complements. For instance, a system which utilizes a larger degree of interconnection between geographically

[3] Fuchs et al. (2012) does not include curtailment of renewable energy, but at high levels of renewable penetration curtailment interacts with the other measures in a similar fashion. For instance, often discussed is a direct comparison of levels of curtailment and the necessity of storage.

disperse variable renewable generators requires less local storage, less curtailment, etc (Delucchi and Jacobson, 2011). Where interconnection is not sufficient, greater degrees of storage, curtailment, flexible generation, and/or demand response may be needed. Options may also act as complements. For example, depending on the technological and economic characteristics of a flexible thermal power plant, it may be utilized for longer periods of supply fluctuation, while fast-reacting storage facilities (i.e. batteries) can provide flexibility over shorter time periods. Thus, all flexibility measures discussed below will be utilized to some extent in the future German power system, particularly as traditional power plants are decommissioned in favor of renewable sources of energy supply.

Below, a brief description of flexibility options discussed in this study is presented.

- **Flexible thermal power plant capacity:** Fossil-fueled and biomass / biogas power plants can provide both flexibility in the spot market and balancing reserve capacity. Plants are required to "ramp" up and down to follow the residual load profile, whereby the ramping speed may act as a constraint. Power plants may also be used for provision of peak supply, particularly during the winter when residual demand due to lack of renewable energy sources may be high. In general, gas-fired plants are considered a good flexibility option due to low capital costs and relatively fast start-up times. Traber and Kemfert (2010) discuss the phenomenon of decreased incentives for flexible thermal power plants as increasing amounts of wind power is integrated into the system. VDE (2012b) discuss the role of flexible power plants for renewable integration until 2020 in the German system.
- **Interconnection within Germany and to other countries:** Physical connection of supply and demand centers via electric transmission lines reduces the chance that local bottlenecks will cause system failure. Further, when renewable (as well as non-renewable) sources are interconnected across large areas, variability in matching supply to demand is generally reduced (Delucchi and Jacobson, 2011). In addition, Germany lies close to countries with large hydro storage potential that would provide additional flexibility to the German system – Norway and Sweden to the north, Switzerland and Austria to the south. A study by Prognos AG gives a helpful overview of these potentials (Ess et al., 2012). Fuchs et al. (2012) estimate that Norwegian reservoirs have around 2,000 times the storage capacity of Germany's installed pumped hydro. Greater interconnection to these countries could allow use of these resources for renewable integration.
- **Curtailment of renewable energy:** The shutting down of renewable power feed-in cuts off renewable electricity generation from the grid in times when renewable energy production exceeds demand. According to current German law, renewable energy that is fed into the grid must be paid for, but may be curtailed. Curtailment in Germany has increased in recent years but has not been utilized to a large extent. In 2012, only 0.33% of total

renewable energy production[4] was curtailed (Bundesnetzagentur and Bundeskartellamt, 2013).

- **Demand-side measures:** Demand-side measures (DSM) involve a temporary decrease or shifting of demand to times when there is less stress on the system. Industry and/or households could be incentivized to shift their demand away from peak times, when less capacity is needed to meet demand. For households, the implementation of these measures necessitates the installment of so-called "smart-meters," which allow for real-time measurement and control of electricity consumption. DSM is explored in the German context in VDE (2012c). Buber et al. (2013) investigate commercial and industrial DSM potential with a focus on southern Germany.
- **Energy Storage:** The storage of energy when it's not needed for times when it is increases the flexibility of the power system and can allow for greater penetration of renewable energy. Storage technologies may either store excess electricity to produce electricity at a different time (power-to-power) or utilize the stored energy for a different purpose – i.e. as heat or for use in the mobility sector. Storage can be used as a flexibility resource over multiple time frames at the electric grid-level or for self-consumption in households, which may also consider grid optimal charging and discharging. Power storage technologies include pumped hydro storage, compressed air energy storage, batteries, flywheels, power to gas, and power to heat. An overview of these technologies is presented in the following section.

1.2 Overview of Energy Storage Technologies

Storage can provide various benefits for the functioning of an electrical grid, including system stability, help in meeting peak demand, the deferral or avoidance of adding or updating grid infrastructure, aiding the integration of large amounts of variable renewable energy (the primary focus of this study), lowering the cost of average dispatch, and other functionalities that improve the stability and resiliency of the electrical grid (Eyer et al.,2010; Denholm et al., 2010). As mentioned, storage can be integrated solely into the electrical grid or for other applications, such as heat or for mobility (for instance electric or fuel cell powered vehicles). In principal storage can be utilized in the short-term (seconds to minutes), daily (hours), and/or seasonally (days to weeks). Storage systems may be installed in a decentralized fashion, located closer to the source of demand and generally smaller in scale, or a centralized fashion, normally located farther away from the demand source and larger in scale. Grid connected storage operations may vary depending on the use they are designed for, but generally systems charge during times of low (residual) demand, coinciding with low energy prices, and discharge, or provide power to the grid, during times of high (residual) demand and relatively higher prices. Batteries installed in conjunction with

[4] Relates to power production from all plants governed by the Renewable Energy Sources Act (EEG).

solar PV at households may be set to optimal charging and discharging cycles that coincide with high and low system stress, respectively, to also contribute to grid stability.

A brief overview of storage technologies discussed in this paper is presented below, based on Simbolotti and Kempener (2012), Fuchs et al. (2012), and the Electric Power Research Institute (EPRI, 2010).

- **Pumped hydro storage:** Pumped hydro storage comprises the vast majority of installed storage worldwide and is considered a mature technology. During times of low demand (and relatively low prices) water is pumped from a low to a high water reservoir. The water is then released, descending to turn turbines which generate electricity. Steffen (2012) estimates potential of an additional 4.7 GW of pumped hydro, compared with about 7.6 GW currently installed in Germany or directly connected to the German transmission grid. Also, the possibility for Germany to connect to neighboring countries' hydro reservoirs (and pumped storage) potential is an explicit part of this study.
- **Compressed air energy storage:** During the charging process, air is compressed, which causes it to heat up. This heat can either be stored (adiabiatic) or removed (diabatic), while the air is stored in an underground cavern for later use. As air is released to drive a turbine and create electricity it must be heated; in the adiabatic process this is accomplished with the stored heat from the compression process, in the diabatic process by burning a fossil fuel. An adiabatic compressed air process could increase the overall efficiency by around 20% and does not require fossil fuels. Germany is currently developing a state of the art adiabatic compressed air storage facility, called ADELE. E.ON has also operated one of two operational compressed air facilities (diabatic) in the world in Germany since 1978, with a rated capacity of 290MW, created to store off-peak electricity from a nearby nuclear power station.
- **Batteries:** Batteries store chemical energy and convert it back to electrical output. There are numerous battery compositions each with a unique performance and cost profile, including lead-acid, nickel-metal-hydride, lithium-ion batteries, and flow batteries, which consist of tanks that determine capacity and a reaction unit (cell stack) that determines the output of the battery. Batteries may be used for multiple applications, at the household level in conjunction with solar PV, with wind turbines, or for applications at the grid-level.
- **Flywheels:** Flywheels store energy in their rotation, able to rapidly release energy as the wheel is slowed by the application of torque. Compared to other storage technologies, flywheels have very low energy storage capacities, but relatively high power ratings. They may be used at the grid level (often in ancillary markets for balancing) or, in principal, for the short-term storage of renewable energy for instance if connected with a wind turbine.
- **Power to Gas:** Hydrogen can be created through an electrolytic process and then compressed and stored in underground caverns, tanks, or fuel cells. Hydrogen may

also be safely injected into the natural gas infrastructure up to a certain concentration between 5% and 20% by volume depending on the system (Melaina et al., 2013). The gas may further be converted to synthetic methane (synthetic natural gas) with the addition of carbon dioxide in a process called methanation. This can then be injected into the existing natural gas pipeline infrastructure for storage and transport. After the conversion process and storage, hydrogen gas and synthetic methane may be utilized to produce electricity at a later time or for other uses, such as the production of heat and/or fuel-cell powered vehicles.

- **Power to Heat:** Thermal energy can be stored with the use of a storage medium to be used later for heating, cooling, or electricity production.[5] The most common type of power to heat storage currently used is for buildings and district heating in cities, using water as the storage medium. Heat pumps, run on electricity, may be used in buildings for efficient heating and cooling. Other types of heat storage include the use of phase change chemicals like molten salt, which has been used with concentrated solar power to store heat, and thermo-chemical storage, which utilizes chemical reactions to store heat.

2. Methodology

To explore and understand views of energy experts on the role of storage for renewable integration, this study utilized semi-structured interviews guided by a questionnaire that was developed for the purpose. The full questionnaire is provided in the appendix, sent by email to participants in advance of the interview.

Experts came from a wide variety of disciplines within the energy field – governmental institutions, industry, business, academia, and think-tanks. Expert individual identities and names are not revealed so that respondents would be willing to express their personal opinion, even if it differed from that of their institution. Individuals who participated in interviews came from the following institutions: Agora Energiewende, Boston Consulting Group, DIW Berlin, Dresden University of Technology, Electric Power Research Institute, Fraunhofer Institute for Wind Energy and Energy System Technology, the German Environmental Ministry (BMU), the International Energy Agency, the International Renewable Energy Agency , Öko–Institut (Institute for Applied Ecology), Potsdam Institute for Climate Impact Research, Technical University Berlin, Vattenfall, and Younicos. In total, 20 experts were interviewed. Experts were asked to fill out the questionnaire and then interviewed (in-person or over the phone) to discuss answers. These interviews were recorded, transcribed, and analyzed. Interviews conducted in German were transcribed by the author into English.

[5] Future applications of high-temperature heat storage may allow thermal energy to be converted back to electricity, for example in a thermal power plant. Such thermal power storage does not play a role in this study.

The questionnaire itself did not largely impose assumptions upon the respondent, other than taking the German government's renewable energy integration goals in the electricity sector as given. By design, individual criteria and assumptions behind responses could be ascertained and discussed through the interview process, where respondents were asked for the assumptions they used to answer questions and why they provided a particular answer.

The questionnaire was divided into five sections – measures to accompany the expansion of renewable energy, necessity of storage, storage technologies, economic and institutional aspects of storage, and additional information. Answers analyzed in detail here come from questions 1.1, 3.2, and section 4 (4.1 to 4.4) as they turned out to be most relevant to ascertain an experts' view over the role of storage in Germany. Answers to other questions in the questionnaire were also examined as they were often applicable to these questions. However, we do not provide a full representation of all answers across the range of experts; this was found to be not particularly useful, as answers were not easily compared or could better be utilized as explaining the background for the experts' view on storage for questions 1.1 and 3.2. For instance, in section 2 the word "necessity" in the context of asking when or what forms of storage would be necessary, was interpreted in multiple ways; however, the assumptions and context in which an expert answered these questions were helpful to explain views presented in the questions analyzed in detail here. Thus, the questions we do analyze provide the best lens to explore and compare expert views and assumptions on the role of storage for renewable integration in the future German power system, as well as the economic, institutional and regulatory framework that governs storage implementation in Germany.

Question 1.1 places storage in the context of other flexibility measures: provision of thermal power plant balancing capacity, expansion of cross-border and domestic transmission, interconnection to countries with large hydro storage capacity (a subset of the previous category), curtailment of renewable energy, demand-side measures, and energy storage in Germany. These options are commonly discussed in the literature (i.e. Timpe et al., 2010; BMU, 2012; BET, 2013). Experts were asked to rank the most promising measures for renewable integration based on a realistic expectation for 2020 and 2050. In addition, experts could also provide an "other" option, i.e. one that was not listed in the question. While these "other" responses could not be compared across experts, they are presented in section 3.1 below.

Question 3.2 asked experts to rank the most appropriate storage technologies for 2020 and 2050: pump storage domestically and internationally, compressed air energy storage, battery storage, flywheels, power to gas, and power to heat. These storage technologies are commonly discussed in the literature (Simbolotti and Kempener, 2012; Fuchs et al., 2012; EPRI, 2010). An "other" category was also presented as an option that could be filled in by experts.

Section 4 explores the economic and institutional framework of storage in Germany, including potential cost reductions for storage technology, whether there is a business case for storage in the wholesale or ancillary markets (both presently and/or in the future), and regulatory supports and hindrances for storage in Germany. These questions helped assess the institutional forces affecting storage, as well as how future changes to market or regulatory frameworks may or ought to affect storage implementation.

Given the time and resources to implement this study, only a selection of experts from diverse institutions could be interviewed. Nevertheless, interviews were conducted across a wide range of institutions, capturing government, industry, business, academia, and think-tanks. Thus, we believe the views summarized and discussed here reflect, overall, the current German conversation and debate at this time.

As in all studies that involve long-term analysis, inherent limitations in the clarity of future outlooks were evident. Respondents recognized the difficulty in describing the energy system towards 2050 which cannot be understated, but was necessary to understand the long-term views of participants.

Further, the importance of how other European countries' energy systems develop and what their effect on the German system may be, as well as the degree of interconnection to the rest of Europe, posed additional complications to rank or describe options presented in the questionnaire. While we specifically ask about cross-border interconnection and connection to European neighbors' hydro power, we do not impose assumptions for other European countries' power sector development. Given the focus on Germany, experts tended to assess neighboring countries' potential to contribute to the integration of renewables in Germany, as requested in the study, but did not specifically detail renewable penetrations and/or degree of interconnection to bordering or farther European countries.

In the analysis below, quotes from the interviews conducted are presented as illustrative examples of a discussed expert outlook. Brackets are inserted in quotations by the author when necessary for clarification and/or brevity.

3. Expert Views on Flexibility Options for Renewable Integration

Overall, respondents ranked the renewable integration options and technologies presented in questions 1.1 and 3.2 using the criteria *feasibility* and *potential*. Potential is defined here as the perceived technical ability of storage to integrate renewable energy. Feasibility refers to the perceived ease of implementation of the technology, taking into account length of time for project installation, public acceptance, economic efficiency, financing, regulatory, and other institutional aspects. The questions asked respondents to rank measures and technologies according to what was "most promising" and "most appropriate" – this was sometimes interpreted in terms of necessity for some respondents, for others, what ought to be a priority. The interview process was thus instrumental for teasing out this distinction and understanding how experts expect storage to play a role for integrating renewables. The time period towards 2020 was universally considered a very short time-period in which feasibility for implementation played a significant role for evaluation. The potential of a given technology in relation to other options was weighed more heavily towards 2050.

Question 1.1 asked for a ranking of measures to accompany renewable energy expansion for 2020 and 2050 according to the "most promising" measures based on a realistic expectation for these time periods. This question is vital for exploring the role of energy storage for renewable integration. In order to discuss the role of storage it is necessary to investigate views on other measures available for system flexibility to give a more complete picture of how these renewable integration options are expected to play a role in the short and long-term. Expert views on each integration measure are synthesized and presented, followed by a discussion and general conclusions drawn in regard to the short and long-term role of storage in the German system.

Provision of Thermal Power Plant Capacity

Across experts, it was agreed that for the 2020 timeframe one of the primary integration measures will be the use of thermal power plants to provide flexibility, similar to today's system. Feasibility in implementation (particularly economic efficiency) was the primary criteria used for this assessment, with one expert noting about traditional thermal power plants:

> "Right now that's still the easiest and most efficient way to do balancing [provide flexibility], in years to come they will [continue to] play a large role […]. I don't see this decreasing fast."

Again, 2020 was considered a very short time-frame and most experts agreed that this traditional method of flexibility in the electric system would largely be in place. It was also generally agreed that the importance of fossil thermal power would drop in the long-term towards 2050. In this case, experts emphasized plants be highly flexible to complement the other measures discussed in this study.

Expansion of Cross-border as well as Domestic (German) Transmission Network Capacity

Most experts emphasized the need and economic efficiency compared to other options of full interconnection within Germany (domestic interconnection) before other options are explored. For 2020 experts rated domestic interconnection a top rank, which usually meant it was both a top priority and top measure to integrate renewables, along with thermal power plants. By 2050 the respective rank either dropped or remained high but this did not usually represent disagreement – most experts assumed that Germany would be largely domestically interconnected by this time. Many experts also expressed concern that domestic connection is currently proceeding too slowly but still expected, to a large extent, full domestic interconnection by 2050. Over the long-term, other options became relatively more important to complement domestic interconnection:

> "It's necessary but not sufficient to upgrade the transmission grid."

In terms of cross-border and further European interconnection, experts generally agreed that 2020 was too short of a time-frame to think about large-scale European interconnection, but towards 2050 this would change (see below for the case of interconnection to countries with large hydro storage capacities). One expert discussed the topic as follows:

> "In the first point my opinion is to see what you can do on the domestic level, because that is our responsibility. One can say it in a negative or positive way. If I have problems I can always say [that]my neighbors will solve the problems of getting by […] but we [Germany] have taken a lead role [among] the European countries, that we want to show them, it's working, the new system is working, and therefore we will have […] to [solve any] national domestic problems."

Most experts expected a larger degree of European integration by 2050:

> "I think to 2050 we are going in Europe like in other countries to a much more integrated grid, where indeed you start to optimize where you have your renewable energy sources across a larger region and match that with demand within a bigger region. I think 2020's too short for that [completion of European interconnection]. But by 2050 I think you get European grid balancing [interconnection]."

Thus, between the choices of interconnection within Germany and cross-border connections, experts agreed that domestic interconnection should (and would) come first, with European interconnection growing in importance at later dates. Some experts additionally stressed that European interconnection doesn't make sense without strong domestic interconnection. In addition, several experts mentioned that though the need for interconnection within Germany should not be a limiting factor, public acceptance issues with building the lines may impede some optimal level of interconnection:

> "I'm thinking grid expansion is quite a cheap and good way to go, but of course within the range of acceptance issues."

Next, expert views on the specific case of interconnection to bordering areas with large hydro storage capacity are explored.

Interconnection to Countries with Large Hydro Storage Capacity (Scandinavia, the Alps)

In the short-term (to 2020) most experts agreed that connecting to countries with large hydro storage capacity would not be a major option for renewable integration due to limited time and feasibility of implementation. In the long-term, there was agreement that this measure would play a greater role when compared with 2020 for renewable integration. However, disagreement occurred over how big a role, relatively, the measure will play. Those who described this option as a more significant alternative over the long-term mentioned fewer obstacles (or none at all) than those who foresaw less of a role. The obstacles that were primarily discussed included public acceptance of the projects in host countries, environmental considerations of converting reservoirs to pumped-hydro storage, which was also related to public acceptance difficulties in these countries, and large financial costs for interconnection, particularly to Scandinavia. One expert talked through reservations for connecting the hydro potential of Norway:

> "Pumped hydro in Norway, that can be a lot of energy, but again that's limited. I'm not sure that the Norwegians are really keen on doing that […] they have quite an intimate relationship to their nature and environment […]. I was talking to someone from Statkraft who was investigating [the issue], they have huge lakes already in a place which they only needed to connect, and then would have […] 500 meters of altitude difference and huge amounts of water. But they said our population loves to go ice-skating on those lakes in winter and if you use them as a reservoir, they won't freeze them anymore [so] they will oppose it. I can imagine that there will be a lot of opposition and looking at the economic situation of Norway they don't need the money. Certainly for Statkraft there would be a good business case but the general public in Norway, why should they do it?"

In addition to public acceptance and environmental obstacles, some experts ranked solutions that could be implemented at the national level higher even over the long-run, expressing skepticism with solutions that require international cooperation. Predictably, this decreased the relevance of this measure for renewable integration in Germany, increasing the importance of measures that can be implemented nationally.

Curtailment of Renewable Energy

The utilization of renewable energy curtailment as a flexibility measure provoked differing views. Some, particularly those who emphasized the economic efficiency of the option, rated the measure highly in comparison to other measures. This is not to say that curtailment was viewed as completely sufficient, just that, to a certain level, it is much cheaper (in some views) than other options:

> "I would not say curtail as much as possible but curtail it up to an economic level where it might make sense."

> "If we're speaking about low levels of curtailment it gets a 1 in both cases [for 2020 and 2050], if we're speaking about high levels of curtailment it gets a 7 in both cases. So what I'm trying to say is, curtailment levels of up to 5% maximum 10% makes sense and should be done, of course always subject to a cost-benefit analysis."

Other experts viewed curtailment as a measure to be utilized after all other options are explored, viewing it as a kind of last resort option:

> "I wasn't too sure about the curtailment of renewable energy because I don't see it as an active measure you take but just as the residual that is left after you have taken all the other measures. So to me it's not a strategy, it's simply what you have to do because you have a limited net [grid constraints] or a limited use, and at some point in time you don't use the electricity anymore."

Nevertheless, experts overall agreed that some curtailment of renewable energy would be necessary and economically efficient with a large amount of variable renewable energy towards 2050. They differed in the extent they believed this was a valuable solution.

Demand-side Measures

Experts expressed a range of views over demand-side measures (DSM), but agreed relatively unanimously that DSM at the household level will not or should not be a huge factor for renewable integration, due primarily to the cost of smart meters, the relatively little impact a shift in household consumption can make for stability of the system, and the relatively little price difference (economic incentive) a household has to change consumption patterns.

Beyond this agreement, expert views on the role and value of demand-side measures varied. Those who believed DSM will play a relatively significant role stressed the idea that with accurate price signals industry is willing, and can with relative ease, shift energy consumption to times of less system stress. They believed this could play a very important role for integrating renewables and creating a more flexible system. A few participants emphasized the fact that DSM can be implemented nationally. In addition, these measures could be implemented within a short time-frame and, in some views, are economically advantageous compared to other options:

> "The [measure] that helps a lot is if you identify load as well as potential of generation on the industry scale - like the glass industry or cement industry; they have processes that last for two hours where they consume 90% of their electricity. So it's not necessary that these two hours should be in the morning time, they could be midday or evenings as well."

In contrast, several participants ranked DSM relatively low for various reasons. One expert was unsure of the impact DSM could make given that it plays a relatively small role in today's market:

> "One thing we don't know about demand side management is how big it will be, that seems to be the next step."

Other participants seemed to classify DSM only at the household level, lowering the ranking. Others simply did not see DSM having a very large impact for renewable integration over the short and long-term.

For some participants DSM also referred to decentralized heat storage, addressed in the storage technology section of this paper below.

Energy Storage in Germany

In the short-term (to 2020), the majority of experts do not see many large-scale storage projects coming online (including pumped-hydro) due to limited time for implementation, cost, and lack of technological development for many technologies. However, some smaller-scale storage was expected in this time-frame, including decentralized heat storage at the district and building level and battery storage at the household and grid level. Overall, experts expected storage to become more important over the long-term (to 2050) for renewable integration compared with the short-term (to 2020).

Beyond these agreements, however, views over the value of storage for renewable integration varied. One of the main drivers of these discrepancies was whether an expert saw the electricity system as continuing to be primarily centralized or moving further towards decentralized production and consumption of electricity. Those who believe the system will become increasingly decentralized saw a greater necessity and development of smaller-scale storage at the local level (such as batteries at the household level), also ranking storage as a more important flexibility option overall. Those who foresaw primarily centralized production of electricity saw greater value for large, centralized storage facilities in the future, but a lower relevance for storage to provide flexibility overall in the future German system.

> "When it comes to electricity storage large is good because of economies of scale, the whole hype about decentralized (storage)…doesn't make a lot of sense."

This view was based on the economic efficiency of building larger storage facilities rather than many smaller, individual facilities. This (more centralized) view came in contrast to those who thought the decentralized "movement" of energy production and consumption would build upon itself, not necessarily entirely due to rational economic reasons:[6]

> "I believe that we will be seeing bottom-up developments starting with very small installations of storage. As we speak, we are seeing the first tendencies that residential storage products or solutions are becoming market ready […] batteries,

[6] Storage at the household level to increase self-consumption can also be implemented for rational economic reasons. This depends on the institutional and economic framework of battery storage implementation in Germany, including electricity prices, grid fees, EEG-related charges, financial storage incentives, cost of the battery, etc.

> home storage, community storage, and I think that be there a systemic need or not, it will just pop up […] over time I think it's quite likely that it will play a role [for system stability]."

In addition, the easier financing of small systems versus the larger amounts of capital for large storage projects was, for some experts, a rationale that storage will be decentralized.

Some experts also discussed the advantage that storage has over other measures because it can be implemented at the national level and international contracts, agreements, and willingness are not necessary. Another advantage experts saw for storage (other than pumped hydro) is that it does not face public acceptance issues:

> "I would say one of the biggest assets of energy storage, battery storage, I'm not talking about pumped hydro, is public acceptance. There's no public acceptance problem."

In the long-term with large renewable penetration, many experts saw the ability of storage to balance seasonal fluctuations of renewable energy as an important characteristic that could be utilized for periods of high residual demand in the winter. This is further discussed in the technology section. Storage was also seen as directly impacting the degree of curtailment that would occur in the future, namely that with more storage less curtailment would be needed, and vice-versa. As seen above, the value of curtailment as a solution to integrate variable renewables varied among experts. The primary influencing factors for how experts viewed storage are explored and presented graphically in the summary section below.

Other

Some experts utilized the "other" category to highlight alternative means of integration either not explicitly listed or a sub-component of one of the listed measures that the expert felt warranted particular emphasis. In this section these answers are not compared and contrasted as is done above but rather attempts to reflect the perspective of the expert view. The renewable integration measures discussed here were mentioned by one expert each.

- **Flexibility from renewables themselves:** This option emphasized the potential of solar and wind to produce energy in a more demand-oriented or grid-oriented manner than is currently practiced today. For instance, solar panels could face east-west rather than north-south, which would give them different production, feed-in, and self-consumption characteristics. The more wind turbines there are on the system, the more value for turbines that can produce electricity with mild winds but not necessarily a large amount when wind speed is high. Incentives for wind developers would need to be put in place for the technological adaptation to make this happen.

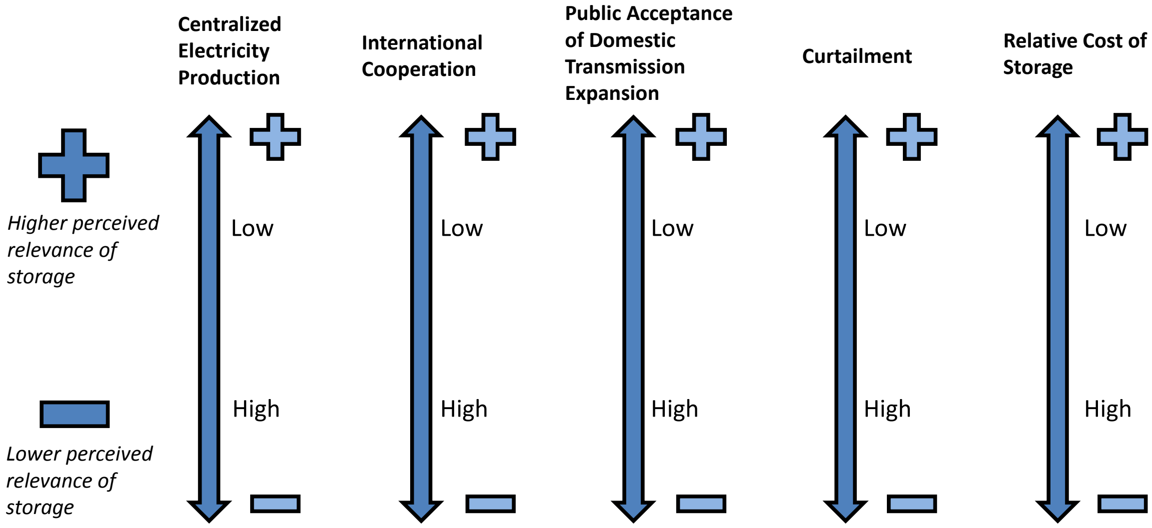
- **Smarter grid solutions and better renewable energy operation:** One expert emphasized the role of a "smart grid" which communicates consumption levels of electricity and the need for renewables to forecast production more reliably. Renewables also need to be responsible for maintaining frequency and voltage of the system, an area that, to-date, has not been a primary focus in renewable development.
- **Flexible conventional power plants:** One expert highlighted the importance of having flexible conventional power (gas and coal plants) for the integration of renewables. The plants should be paid for flexibility and price levels should be linked to the grid stabilization level.
- **Short-term storage (grid level):** Short-term storage (i.e. battery storage) at the grid level can be utilized for ancillary services in Germany including balancing, black start capability and/or provision of reactive power, largely accomplished in the current system with conventional power plants. These fast reacting ancillary services would be able to replace base load or "must-run" power plants, enhancing economic efficiency of the system while still ensuring voltage and frequency reliability in a system of high renewable penetration.
- **Shift to "peak-load" technologies for conventional plants:** As more variable renewables come online, conventional plants will have fewer hours to recoup their costs. Thus, investment in conventional technologies should focus on power plants that are flexible and expected to run at peak times or when renewable supply does not cover demand.

Summary of Expert Views on Measures for Renewable Integration and the Role of Storage

Overall, storage was viewed as an option for system support where other options are limited. In the short-term (to 2020) experts expected traditional measures of flexibility, namely thermal power plants and strengthened domestic interconnection in Germany, to continue to play a primary role for system stability. Most experts expected virtually full interconnection within Germany to transport renewable electricity production to centers of demand towards 2050. It was agreed that storage will grow in importance over the long-term with increasing amounts of variable renewable energy.

Further views on the role of storage were heavily influenced by whether an expert expected increasingly decentralized production of energy versus centralized production. Increasing amounts of decentralized energy production led experts to emphasize the importance of storage more than those who believed production and consumption of electricity would continue to be largely centralized. In addition, for those who rated storage highly in the long-term, the fact that storage can be a national option and used for seasonal fluctuation of renewable energy supply were important factors. Experts from both the decentralized and centralized view recognized the value storage can bring to balance seasonal fluctuations of renewable energy over the long-term. The most influential criteria for how storage was perceived over the long-term are presented graphically below, determined to be the degree of centralized electricity production, international cooperation, public acceptance of domestic transmission expansion, curtailment, and the relative cost of storage compared to other flexibility options.

Figure 2. Influential Long-Term Criteria for Expert Views on Storage in Germany



As increasing amounts of renewable energy come online in the German system, a high degree of decentralized electricity production (relatively lower centralized production) leads to a higher perceived relevance for the role of storage for integration of renewables. Lack of international cooperation also leads to a higher perceived relevance of domestic storage – similarly, low levels of public acceptance for some amount of domestic interconnection, low levels of curtailment, and a relatively low cost of storage compared to other flexibility options all lead to a higher perceived relevance of storage to accommodate renewable expansion. The graphic is not meant to be all-inclusive, but it does illustrate the primary criteria found in this study and the complexity of how storage is viewed in the German electrical system. Of course, views for each category did not land on one side or the other, and depending on how an expert weighs, relatively, each issue, his/her outlook will ultimately be pushed in one direction or the other. It was clear, however, that whether an expert saw future electricity production as increasingly decentralized or centralized was a universally influential factor for an experts' view on storage overall.

Expert Views on Energy Storage Technologies

Views on storage technology should be examined through the lens of how storage is perceived along with the other flexibility options, presented above. Within this context, we see that most experts expected storage to play a less significant role for system flexibility than thermal power plants and interconnection in the short-term due to feasibility of implementation, with the primary exceptions of power to heat and batteries (see sections below). Long-term views varied by technology and are presented here. It is important to remember that the technologies explored provide different services and abilities to integrate renewable energy. For instance, batteries provide short-term flexibility while power to gas can provide longer-term (seasonal) flexibility. Thus, it is not the intention here to say that one technology is more important than the other, but rather to understand how experts view a technology's ability to integrate renewables in Germany, and how those views vary.

New Pump Storage in Germany

A majority of participants saw limited potential for new pumped hydro storage in Germany. A typical statement was:

> "It would be nice but I don't see it as realistic, at least not within Germany."

Current hydro storage capacity and a small number of additional projects were expected to be sufficient towards 2020. A few participants, however, saw relatively significant potential in coming years, up to 10-12 GW. Thus, depending on the experts' view of hydro storage potential, which in the majority view is limited due to techno-economic constraints and/or public acceptance issues, experts were either highly optimistic or pessimistic about new pumped storage in Germany contributing to renewable energy integration. Most experts believed existing pumped hydro capacity was sufficient to integrate renewables to 2020 (along with thermal power plants, discussed above).

Use of Hydro Storage in Other Countries

Expert views here reflected the discussion above (see section on expert views on measures for renewable integration). For those who thought this option was feasible, the option was ranked as a top storage technology towards 2050. For those who did not, the option was not expected to play a significant role for neither the short nor long-term.

Compressed Air Energy Storage and Power to Gas

Experts agreed that compressed air energy storage (CAES) and power to gas technology would not have a significant impact by 2020. In general, CAES was seen in less favorable terms than other technologies, particularly in comparison with power to gas. This was primarily due to the notion that CAES can store less energy and gas has existing natural gas infrastructure that can be utilized for storage and transportation. Further, several experts cited the fact that compressed air facilities will likely be limited by salt cavern availability, primarily located in the north of Germany. A few experts noted that public acceptance issues for storing air under the ground could be problematic or limiting for this technology. These perceptions tended to drop compressed air's relative importance in the long-run, where seasonal flexibility to compensate for periods of high residual demand was an influential factor for expert views. The gas could also be used for electricity production, heating, or in fuel cell powered vehicles, seen as creating additional opportunities for flexibility and profit streams in a renewable economy.

> "Power to gas is a lot more relevant in the discussions at the moment. The big advantage in power to gas is that the storage is already there, you have the pipelines. You've also got a good combination to other sectors, [for instance] power to gas [can also be] used […] for hydrogen cars or for heating."

A few experts did view compressed air as playing a relatively significant role in the future German power system, citing the fact that a compressed air facility is already integrated into the market in Germany and that adiabatic compressed air pilot projects would ultimately improve efficiency and sustainability of the process. Overall, however, prospects for the technology in the long-term were less optimistic than other options. Those experts who rated compressed air highly in the long-term saw restrictions to power to gas technology and relative advantages for compressed air. The expert view presented below saw adiabatic compressed air as playing an important role:

> "Adiabatic compressed air facilities have relatively high efficiencies, and when I make electricity from gas and then burn it, the efficiency will go down […]. I've looked at the effect of efficiency [on cost], and efficiency has a huge influence. 80% compared to 50% has a huge effect."

However, as mentioned a majority of experts saw limitations to CAES and relative advantages for power to gas that caused them to rate power to gas highly for long-term seasonal storage. The few experts who were generally pessimistic over the prospects of power to gas primarily believed the process was too inefficient to economically solve the seasonal storage challenge. This was coupled with a more optimistic view of compressed air storage technology, particularly adiabatic compressed air.

Batteries

Expert outlooks on battery storage were mixed, largely hinging on whether an expert saw the future electricity system as increasingly decentralized or remaining centralized. Those experts who expected decentralization foresaw an important role for battery storage in both the short and long-term, particularly in combination with solar PV systems. These experts also emphasized that the electricity system in Germany is developing in a way that supports the economics of household battery systems – namely rising electricity prices and decreasing battery costs. Thus, most experts saw battery storage as capable of being implemented in Germany to a greater extent towards 2020 in comparison with other options due to perceived higher feasibility of implementation and advantages in financing smaller projects. In the long-term towards 2050, batteries were seen as important for renewable integration by those experts who foresaw a more dominant role for decentralized energy production, particularly optimal solar integration and congestion relief at the distribution level. Those who expected a more centralized energy production system in the future did not say batteries would be unimportant, but tended to rank other technologies higher due to perceived higher potential of these technologies to integrate renewables.

Flywheels

Most experts were either unfamiliar with flywheel technology or did not believe it would ever play a major role in the German system. Overall, respondents did not provide strong opinions about the role of this technology.[7]

Power to Heat: Heat Storage, Including Heat Pumps

The implementation and role of power to heat in the German power system was an area of overall agreement found in this study. Experts believed the technology could be implemented towards 2020 and would remain useful in 2050. Despite the measure receiving high marks for feasibility of implementation given the important role heat plays in Germany, its potential for the integration of large amounts of renewable energy was seen as limited.

> "[Power to heat] is relatively quick to implement and economical […]. But it won't, alone, make the Energiewende successful."

Thus, power to heat was universally seen as cost-effective and feasible, but with limited potential to aid the integration of renewable energy.

Other

Some experts utilized the "other" category to emphasize the more significant role that non-storage integration measure would play in comparison with storage technologies, discussed above. Several experts mentioned the possibility of novel or less-developed storage technologies coming online in the future system depending on technological development and progression of market and regulatory forces. 2050 was seen as a long enough time period for unforeseen technological development to occur for technologies discussed above as well as novel technologies currently in the beta stage of development. The majority of participants, however, did not fill in this category.

Summary of Expert Views on Energy Storage Technologies

For storage technologies, the largest areas of agreement from experts occurred over power to heat and power to gas storage technologies. Increased implementation of power to heat storage was viewed as necessary, cost-efficient, and helpful but limited for the integration of large amounts of renewables in Germany. Power to gas was viewed as one of the best

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[7] Due to greater concerns over supply quality / electric system reliability in the United States of America, flywheel technology receives much greater interest there in comparison with Germany. See Borden and Schill (2013).

options for seasonal storage in the long-term and was often contrasted favorably to compressed air energy storage. Power to gas was viewed as particularly useful for seasonal storage because a storage and pipeline network for the gas already exists and would not need costly updates. Further, experts believed that relatively more energy could be stored compared to other technologies and integrated with other parts of the future renewable economy (i.e. mobility). Batteries for the integration of PV was largely seen as possible by 2020, with experts who foresaw increasing decentralization of electricity production viewing this technology very favorably overall for the integration of renewables. A graphical depiction of long-term views of the role of storage technologies in Germany is presented below.

Figure 3. Long-Term Expert Views on Storage Technologies for Renewable Integration

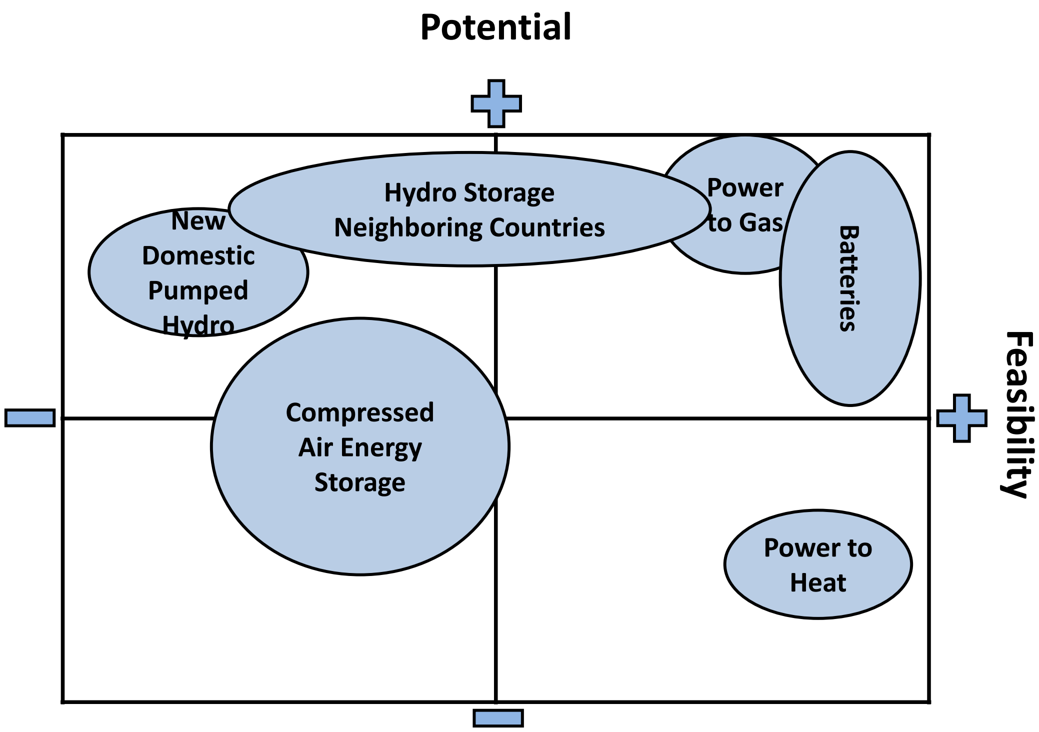

Figure 3 graphically illustrates long-term expert views on the storage technologies discussed in this study. “Potential” refers to the perceived technical ability of the technology to integrate renewable energy. “Feasibility” refers to the perceived ease of implementation of the technology, Including public acceptance, economic efficiency, financing, regulatory, and other institutional aspects. Alternative storage technologies affect how an expert views a singular technology – for instance, experts who believed pumped hydro or international hydro reservoirs would provide a large amount of system flexibility in the future saw less relevance for other long-term storage technologies. Expert views did of course range, particularly in regard to batteries and pumped hydro in neighboring countries. While views over feasibility for connecting to pumped hydro in other countries ranged, the perceived potential of batteries to help integrate renewables varied among respondents. The graphic is useful to visualize overall expert views on storage technologies in Germany, but should not be used to claim one technology as "better" than another. For instance, different technologies will be implemented for respective advantages from an economic, technical, and social standpoint for specific applications. Some battery compositions are better-suited from an economic and technical standpoint for short-term residual demand fluctuation, whereas power to gas may be favorable to compensate for seasonal fluctuations of renewable energy. Utilization of technologies will depend on market and policy framework developments which determine the profitability and usefulness of technologies over the long- term.

4. Expert Views on Economic and Institutional Aspects of Storage

In this section, participants were asked to discuss potential cost improvements for storage technology, the market for storage, market and regulatory barriers, and areas where improvements for regulation or additional incentives for storage may be necessary.

There was general consensus that batteries and power to gas would achieve cost improvements in the future; some experts believed batteries would achieve significant cost reductions in the short to medium-term. By contrast, hydro storage was not expected to achieve significant cost reductions over the long-term.

Experts agreed that the business case for storage was currently quite limited at the wholesale market level. This conclusion was derived from the spread between high and low prices in this market, seen as insufficient for storage operators to make a profit:

> "Today […] for a large storage system there is no incentive because [wholesale] prices have too little volatility, peak prices are too low, […] so it doesn't make sense to invest in storage. For decentralized [storage] the situation is different because there the incentives are different."

However, several experts believed that there is a sufficient business case for storage in the ancillary/balancing services market in Germany.

With regard to decentralized PV storage, experts generally saw increasing incentives for the installation of battery systems with PV due to increasing consumer electricity prices and decreasing solar PV feed-in tariffs. Several also mentioned a new investment subsidy (which was still in the planning stage for some of the interviews) for storage with PV installations, currently implemented by the German Environmental Ministry (BMU) and KfW Bank,[8] which could also help spur deployment of decentralized storage systems.

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[8] Worth €25 million in 2013. 30% of the installation cost may be covered with a grant from the German government, the remaining 70% with a low-interest loan from KfW Bank. (BMU, 2013; Borden and Schill, 2013)

> “[For decentralized systems] you don’t see the spot market prices, the customers only see their [retail price] and this tariff has to be compared with PV generation costs. And there you have a difference. And with falling generation costs of PV and increasing tariffs of electricity, and without any change in market design for example for the grid fees, for the taxes, this difference is increasing and there’s an incentive to invest in decentralized [power supply].”

In this context the grid fee issue came up often, with many experts suggesting that the variable structure of these fees ought to be changed in the future because consumers with high levels of self-consumption due to storage would not be paying a fair share of grid fees, raising rates for everyone else. Therefore, it was generally agreed that grid fees should not be charged according to how much electricity is consumed from the grid in kilowatt hours, as is currently practiced. How, exactly, these grid fees would be assessed in a fair manner while still encouraging conservation was not discussed in the interviews – they could be based, for instance, on the maximum kilowatt (kW) usage a household requires from the grid over the course of a year.

> “What will not work, I would say, [is that] you pay your grid fees on a kilowatt hour basis [in the future]. So, those people who install PV for their own consumption, they reduce their […] contribution to total grid costs. This system has to be changed to a flat tariff.”

At the same time, payment of grid charges on a non-variable (per kWh) basis was acknowledged to decrease incentives to own solar PV and storage in the first place.

Another aspect that was universally discussed and agreed upon by experts was that regulatory uncertainty for storage operation must be clarified.

> “The role of storage in grid operation is not clearly defined. Storage can be a consumer, producer, and component of the grid at the same time. Adjustment of the EnWG [Energiewirtschafts Gesetz] is necessary.”

> “They [the German government] should at least clarify [their] perspective on how storage will be integrated in future markets so that operators can have a vision of what might be there in the future and how they can operate their storage [facility].”

The question of whether the market should be adapted to account for the benefits of storage elicited different responses. This part of the questionnaire often provoked discussion about a capacity market in Germany, seen as likely to be implemented in the short-term. Though experts did not give specific recommendations on how the capacity market should be structured, many mentioned that it should take into account and pay for the benefits that storage (and other flexibility measures) has to offer, also at the European level in the future. A few experts talked about the idea that storage, in addition to other measures of flexibility, could provide an alternative to grid expansion. TSO’s could be allowed to own storage (and other flexibility options other than interconnection) or storage could be a national asset that would supply system security as part of a strategic reserve for future system stability. Overall, these experts believed a future market design or regulatory change (in addition to clarity for how storage is regulated) should and would aid the implementation of storage in order to integrate renewables in the future.

On the other end of the spectrum, some participants believed market and incentive structures should not be fundamentally altered to specifically incentivize implementation of storage.

> "[…] if incentives are not there today that is just showing that the system does not need storage today. And we shouldn't build any. We should not mess around with the market design to show incentives that we believe should be there – that's the wrong way to think about it I believe."

Summary of Expert Views on Economic and Institutional Aspects of Storage

In summary, experts saw a limited business case for storage at the wholesale (energy) market level in both the short and long-term because price spreads are not expected to be sufficient. However, several participants did see a business case for storage in ancillary markets for balancing. Experts agreed that variable (kilowatt hour) grid charges would need to be altered so that they remain sufficient even as some consumers use less electricity from the grid in some periods of the year when coupling battery storage with solar PV. Exactly how fees would be assessed was not discussed and the suggestion was acknowledged to decrease incentives to install battery storage in the first place. It was also uniformly agreed that regulatory treatment of storage ought to be clarified. While some experts believed the current market design provides sufficient incentives, others believed a capacity market or strategic reserve should specifically take into account and pay for the benefits of storage assets.

5. Conclusion

In conclusion, the study presented here reveals important insights about how experts view the role of storage for renewable energy integration in Germany. First, storage should always be viewed in the context of other measures for renewable integration – no single measure appears to be sufficient in the long-term and most of them will be utilized to some extent. Some measures will, however, take priority in the short and/or long-term and public policy must recognize assumptions prevalent in the field in order to optimize decision-making.

Overall, experts generally viewed the role of storage in the short-term as limited, where traditional measures of flexibility, namely thermal power plants and strengthened domestic interconnection in Germany, will continue to play the primary role. However, the relative importance of storage increased over the long-term towards 2050 across experts. Several criteria were identified (see figure 2) that experts weighed to determine the relative value of storage in the future German system with increasing amounts of fluctuating renewables; namely, the degree of centralized electricity production, international cooperation, public acceptance of domestic transmission expansion, renewable curtailment, and relative cost developments of storage technology. Whether an expert saw future electricity production as decentralized or centralized was one of the biggest drivers for how the role of storage was viewed. Experts who expected German energy production to be more decentralized viewed storage as a more important and helpful flexibility option. Predictably, domestic storage assets were viewed as more relevant by experts who saw less of a role for international cooperation, including the use of hydro storage in neighboring countries.

For storage technologies, the largest areas of agreement from experts occurred over power to heat and power to gas storage technologies. Power to heat was seen as highly feasible but limited in potential to integrate renewables, and was expected to be implemented over the short-term. Power to gas was seen as the most promising technology in the long-term for seasonal storage in a system with very high renewable penetration, one of the primary drivers for the development of storage agreed upon across experts. Batteries were seen as a relatively developed storage technology with beneficial characteristics for integration of solar PV at the distribution level.

Experts agreed that there is currently a limited business case for storage in the German wholesale market due to insufficient price spreads, but a business case was seen in ancillary markets. Regulatory treatment of storage should be clarified, and grid fees ought to be changed from a variable kilowatt hour charge to eliminate perverse incentives for households installing battery storage to increase self-consumption of electricity. While some experts believed the market should be fundamentally altered to recognize the benefits of storage assets via a capacity market or long-term strategic reserve, others believed the current market design would provide sufficient price signals to incentivize flexibility in order to integrate renewables.

The study here attempted to shine a light on the current conversation in Germany such that the prevailing criteria and assumptions regarding flexibility measures and the role of storage within them could be seen, discussed, and evaluated. We thus allow policymakers and interested stakeholders to examine the prevailing discourse in Germany. Considering Germany’s leading global role in the development of renewable energy, stakeholders from various regions and countries around the world will also benefit from an understanding and analysis of this discussion.

The electricity system transforms slowly and deliberately, guided by policy, market, and technological developments; understanding assumptions and discourse about the current system and its future outlook is vital to optimally shape its formation. We hope to have contributed to this understanding such that additional flexibility options, among them storage, may be efficiently implemented to integrate large amounts of renewable electricity without sacrificing reliability.

References

BET (2013): Möglichkeiten zum Ausgleich fluktuierender Einspeisungen aus Erneuerbaren Energien.Studie im Auftrag des Bundesverbandes Erneuerbare Energie. BET Büro für Energiewirtschaft und technische Planung GmbH. Bochum, April 2013.

BMU (2012): Bericht der AG 3 Interaktion an den Steuerungskreis der Plattform Erneuerbare Energien, die Bundeskanzlerin und die Ministerpräsidentinnen und Ministerpräsidenten der Länder.Berlin, 15.10.2012.

BMU (2013): Neues Förderprogramm für dezentrale Batteriespeichersysteme. Federal Ministry for the Environment. Available at: http://www.erneuerbare-energien.de/die-themen/foerderung/neues-foerderprogramm-fuer-dezentrale-batteriespeichersysteme/ [Accessed: September 2, 2013]

BMWi, BMU (2010): Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply. Berlin, 28 September 2010.

Borden, E., Schill, W.-P. (2013): Policy Efforts for the Development of Storage Technologies in the U.S. and Germany. DIW Discussion Paper 1328.

Buber, T., Gruber, A., Klobasa, M., von Roon, S. (2013): Lastmanagement für Systemdienstleistungen und zur Reduktion der Spitzenlast. *Vierteljahrshefte zur Wirtschaftsforschung* 82(3), Energiewende in Deutschland – Chancen und Herausforderungen, pp. 89-106.

Bundesnetzagentur, Bundeskartellamt (2013): Monitoringbericht 2013. Monitoringbericht gemäß § 63 Abs. 3 i.V.m. § 35 EnWG und § 48 Abs. 3 i.V.m. § 53 Abs. 3 GWB. Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen und Bundeskartellamt. Bonn, Stand: Dezember 2013.

Dapeng, L., Weiwei, W. (2009): Barriers and incentives of CCS deployment in China: Results from semi-structured interviews, *Energy Policy* 37(6), 2421-2432.

Delucchi, M., and Jacobson, M. (2011): Providing All Global Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies, *Energy Policy*, 39(3), pp. 1171-1172.

Denholm, P.; Ela, E.; Kirby, B., and Milligan, M.,(2010): Role of Energy Storage with Renewable Electricity Generation. National Renewable Energy Laboratory. TP-6A2-47187.

Denholm, P., Hand, M. (2011): Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. *Energy Policy* 39(3), 1817-1830.

DLR et al. (2012): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. DLR, IWES, IFNE. Stuttgart, Kassel, Teltow.

Ess, F., Haefke, L., Hobohm, J., Peter, F., Wünsch, M. (2012): Bedeutung der Internationalen Wasserkraft-Speicherung für die Energiewende. Prognos AG. October 9, 2012.

EPRI (2010): Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. Electric Power Research Institute, Palo Alto, CA, 2010.

Eyer, J., Corey, G., Sandia National Laboratories (2010): Energy storage for the electricity grid benefits and market potential assessment guide: a study for the DOE energy storage systems program. Available at: http://www.sandia.gov/ess/publications/SAND2010-0815.pdf.

Feldpausch-Parker, A., Chaudhry, R. Stephens, J., Fischlein, M., Hall, D., Melnick, L., Peterson, T.R., Ragland, C., Wilson, E. (2011): A comparative state-level analysis of carbon capture and storage (CCS) discourse among U.S. energy stakeholders and the public, *Energy Procedia* 4.

Fuchs, G., Lunz, B., Leuthold, M., Sauer, D. (2012): Technology Overview on Electricity Storage: Overview on the Potential and on the Deployment Perspectives of Electricity Storage Technologies. Smart Energy For Europe Platform, RWTH Aachen, June 2012.

Horton, J., Richard, M., Struyven, G. (2004): Qualitative Research: Experiences in Using Semi-Structured Interviews. Chapter 20 of The Real Life Guide to Accounting Research: A Behind-the-Scenes View of Using Qualitative Research Methods. Elsevier.

IEA (2011): Harnessing variable renewables: A guide to the balancing challenge. International Energy Agency., Organization for Economic Co-operation and Development. Paris: OECD/IEA.

Melaina, M.W., Antonia, O., Penev, M. (2013): Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. National Renewable Energy Laboratory. NREL/TP-5600-51995, March 2013. Golden, CO.

Nooraei, M., Littlewood, J.R., Evans, N.I., (2013): Feedback from Occupants in 'as Designed' Low-carbon Apartments, a Case Study in Swansea, UK. *Energy Procedia* 42, 446-455.

Rogers, J.C., Simmons, E.A., Convery, I., Weatherall, A. (2008): Public perceptions of opportunities for community-based renewable energy projects, *Energy Policy* 36 (11), November 2008, 4217-4226.

Talja, S. (1999): Analyzing Qualitative Interview Data: The Discourse Analytic Method, *Library & Information Science Research* 21 (4), November 1999, 459-477.

Schill, W.-P- (2013a): Systemintegration erneuerbarer Energien: Die Rolle von Speichern für die Energiewende. *Vierteljahrshefte zur Wirtschaftsforschung* 82 (3), 61–88.

Schill, W.-P. (2013b): Residual Load, Renewable Surplus Generation and Storage Requirements in Germany. DIW Discussion Paper 1316.

Simbolotti, G., Kempener, R. (2012): Electricity Storage Technology Brief. IEA-ETSAP and International Renewable Energy Agency (IRENA) Technology Policy Brief E18. April 2012.

SRU (2011): Wege zur 100% erneuerbaren Stromversorgung. Sondergutachten des Sachverständigenrates für Umweltfragen. Berlin, January 2011.

Steffen, B. (2012): Prospects for pumped-hydro storage in Germany. *Energy Policy* 45, 420-429.

Timpe, C., Bauknecht, D., Koch, M., Lynch, C. (2010): Integration of electricity from renewable energy sources into European electricity grids. European Topic Center on Air and Climate Change. ETC/ACC Technical Paper. December 2010.

Traber, T., Kemfert, C., (2011): Gone with the wind? — Electricity market prices and incentives to invest in thermal power plants under increasing wind energy supply. *Energy Economics* 33(2), 249-256.

Ruester, S., J. Vasconcelos, X. He, E. Chong und J.-M. Glachant (2012): Electricity Storage: How to Facilitate its Deployment and Operation in the EU. THINK Topic 8. Final Report. Florence, June 2012.

Schaefer, M., Lloyd, B., Stephenson, J, (2012): The suitability of a feed-in tariff for wind energy in New Zealand—A study based on stakeholders' perspectives. *Energy Policy* 43, April 2012, 80-91.

VDE (2012a): Energiespeicher für die Energiewende. Speicherungsbedarf und Auswirkungen auf das Übertragungsnetz für Szenarien bis 2050. ETG-Task Force Energiespeicherung. VDE, Frankfurt.

VDE (2012b): Erneuerbare Energie braucht flexible Kraftwerke – Szenarien bis 2020. ETG-Task Force Flexibilisierung des Kraftwerksparks. VDE, Frankfurt.

VDE (2012c): Ein notwendiger Baustein der Energiewende: Demand Side Integration Lastverschiebungspotenziale in Deutschland. ETG-Task Force Demand Side Management. VDE, Frankfurt.

Appendix

<u>Energy Storage in the Context of the Energiewende: An Expert Survey</u>

Please read through the entire questionnaire before answering the following questions. Participants may not have an opinion for every question. Individual names and organizations will <u>not</u> be linked with expressed opinions in the final summary of this research, and we are looking for your opinion – not that of a larger organization. Thank you very much for your contribution.

Within the framework of the so-called Energiewende, the German government has embarked on ambitious goals for the development of renewable energy. By the year 2020, at least 35% of gross electricity demand should come from renewable sources. By the year 2030 this portion should increase to 50%, by 2040 to 65%, and by 2050 to 80%. These goals can only be reached when fluctuating sources - wind and solar photovoltaic power - can be utilized to a large extent. Given this background, please answer the following questions about the role of energy storage in Germany's electricity market**.** Answers may always be qualitatively supplemented, for example by specifying underlying assumptions.

1 Measures to accompany the expansion of renewable energy

1.1 In your opinion, which measures accompanying the expansion of renewable energy for the year **2020/2050** are most promising? Based on your realistic expectation, please rank from 1 (most appropriate) to, if necessary, 7 (least appropriate) respectively for each year:

Rank		**Strategy**
2020	**2050**	
		Provision of thermal power plant balancing capacity
		Expansion of cross-border as well as domestic (German) transmission network capacity
		Interconnection to countries with large hydro storage capacity (Scandinavia, the Alps)
		Curtailment of renewable energy
		Demand-side measures
		Energy storage in Germany
		Other:

2 Necessity of Energy Storage

2.1 From what year do you think additional energy storage is needed in Germany?

□ 2020

□ 2030

□ 2040

□ 2050

□ Never

2.2 If possible, please specify: How much additional storage capacity do you think is necessary (in GW and/or GWh)?

2020: ___

2030: ___

2040: ___

2050: ___

□ None

For the following questions (2.3 to 3.1), please select one response when possible.

2.3 Are there regions where storage is particularly necessary?

□ In Northern Germany

□ In Southern Germany

□ In another region:_____

□ No

2.4 What type of storage will be particularly necessary?

□ Storage for short-term compensation (seconds to minutes)

□ Daily storage (hours to days)

□ Seasonal storage (weeks to months)

□ Other Storage:______

□ None

2.5 What application of storage will be particularly necessary?

□ Storage of temporary excess electricity

□ Provision of peak demand

□ Other: ___

□ None

3 Storage Technologies

3.1 Are storage needs best met primarily by large, central storage facilities, or by small, decentralized storage facilities?

□ Large central storage facilities

□ Small, decentralized storage facilities

□ Other: ___

□ None

3.2 What storage technologies for the year **2020/2050** do you believe are most appropriate? Please assess from 1 (the most appropriate) to, if necessary, 9 (least appropriate) respectively for each year:

Rank		**Technology**
2020	**2050**	
		New pump storage in Germany
		Use of hydro storage in other countries (reservoirs, pump storage)
		Compressed air energy storage, specify if possible, diabatic or adiabatic:
		Batteries, specify if possible, battery composition:
		Flywheels
		Power to Gas; specify if possible, with/without Methanisation:
		Power to Heat: heat storage, including heat pumps
		Other:
		Other:

4 Economic and Institutional Aspects of Storage

4.1 Which storage technologies offer significant potential for long-term cost reduction?

4.2 Does the electricity market presently and/or in the future provide sufficient incentives for storage (i.e. is there a business case for storage)? In which part of the market and/or application areas do you see the best business case for storage (i.e. wholesale, system balancing, ancillary, other)?

4.3 What regulatory / institutional measures promote energy storage in Germany?

4.4 What regulatory / institutional measures impede the use of energy storage within Germany and/or from abroad? How could they be improved?

5 Additional Information

5.1 If possible, please explain your essential underlying assumptions in answering the questions above. What future developments do you expect in Germany with regard to the following categories?

Category	Low	Medium	High
Electricity Demand	□	□	□
Fossil Fuel Prices	□	□	□
CO_2 Price	□	□	□
Electricity Prices	□	□	□

5.2 Are there any other issues or assumptions that you think are relevant but not included in this questionnaire / interview?