DIW Economic Bulletin

10 2015

ECONOMY. POLITICS. SCIENCE.

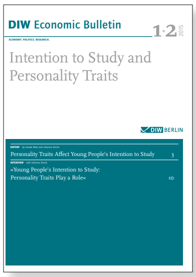
Power Storage for the German Energy Transition

DIW BERLIN

DIW BERLIN

DIW Berlin — Deutsches Institut für Wirtschaftsforschung e. V.
Mohrenstraße 58, 10117 Berlin
T +49 30 897 89 -0
F +49 30 897 89 -200

Volume 5
4. March, 2015
ISSN 0012-1304



The DIW Economic Bulletin contains selected articles and interviews from the DIW Wochenbericht in English. As the institute's flagship publication, the DIW Wochenbericht provides an independent view on the economic development in Germany and the world, addressing the media as well as leaders in politics, business and society.

The DIW Economic Bulletin is published weekly and available as a free download from DIW Berlin's website.

THE NEWSLETTER FROM THE INSTITUTE

The DIW Newsletter in English provides the latest news, publications and events from the institute every two weeks. Furthermore we offer 'New Issue Alerts' for the DIW Economic Bulletin and the DIW Roundup.

>> Subscribe to DIW Newsletter in English at: **www.diw.de/en/newsletter**

NEXT WEEK IN DIW ECONOMIC BULLETIN

DIW Berlin's Spring Economic Forecast

Publishers
Prof. Dr. Pio Baake
Prof. Dr. Tomaso Duso
Dr. Ferdinand Fichtner
Prof. Marcel Fratzscher, Ph.D.
Prof. Dr. Peter Haan
Prof. Dr. Claudia Kemfert
Dr. Kati Krähnert
Prof. Karsten Neuhoff, Ph.D.
Prof. Dr. Jürgen Schupp
Prof. Dr. C. Katharina Spieß
Prof. Dr. Gert G. Wagner

Editors in chief
Sabine Fiedler
Dr. Kurt Geppert

Editorial staff
Renate Bogdanovic
Andreas Harasser
Sebastian Kollmann
Dr. Claudia Lambert
Dr. Anika Rasner
Dr. Wolf-Peter Schill

Translation
HLTW Übersetzungen GbR
team@hltw.de

Layout and Composition
eScriptum GmbH & Co KG, Berlin

Press office
Renate Bogdanovic
Tel. +49-30-89789-249
presse@diw.de

Sale and distribution
DIW Berlin

Power Storage: An Important Option for the German Energy Transition

By Wolf-Peter Schill, Jochen Diekmann and Alexander Zerrahn

The German energy transition makes it necessary to increase flexibility in the electricity system. Different forms of power storage may play a part in this, yet there is competition with other options on the production or demand side. In the short term, the further expansion of electricity generation from fluctuating renewables will be possible in Germany without additional power storage facilities. In the longer term, however, storage requirements will depend strongly on specific circumstances and are therefore difficult to predict. A model-based analysis shows that requirements for power storage rise sharply when the share of renewable energies is very high, particularly if other potential sources of flexibility are less developed. If options such as flexible generation of electricity from biomass, the enhancement of demand-side flexibility, or cross-border contributions to integrating renewable energies develop less favorably than is frequently assumed today, then additional electricity storage facilities will be required and economically beneficial in the long term. For this reason, supporting the development of power storage will be a useful component of a policy designed to safeguard the energy transition for the future. Policy-makers should aim for technological progress and cost reduction in power storage, primarily by means of continued and broad-based support for research and development. At the same time, policy should enable a level playing field for competition among the flexibility options in the various areas of application, for example on the control reserve market.

The German government has set itself ambitious long-term targets for the utilization of renewable energy sources. In the electricity sector, around 50 percent of Germany's gross electricity consumption is to be covered by renewables by 2030, rising to at least 80 percent by 2050.[1] This will necessitate considerable further expansion of power-generation capacities, especially from wind energy and photovoltaics — where production is subject to weather-related, diurnal, and seasonal fluctuations.

Against this backdrop, it seems plausible to assume a growing importance for power storage, which can contribute to balancing out electricity supply and demand. Yet several recent studies suggest that in the short to medium term, it is only in particular niches that additional power storage capacity may be required.

Model analyses on the requirements and market effects of power storage facilities were carried out at DIW Berlin as part of a three-year research project.[2] This report presents partial results of the work, with a focus on long-run power storage requirements and the role of policy-making in further support for power storage facilities.

Continued Expansion of Renewables Increases Need for Flexibility

Electricity supply and demand have to be constantly aligned, in both time and space.[3] Consequently, greater

1 See Section 1 of the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG 2014), Bundesgesetzblatt, July 24, 2014.

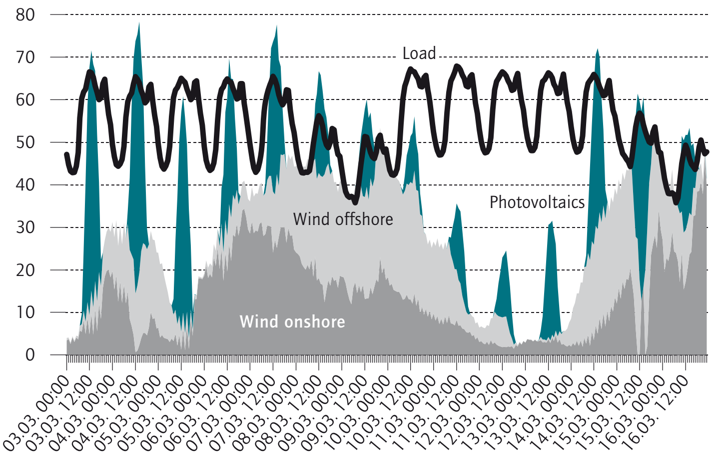
2 The research project Storage for Renewable Energy Sources (StoRES) was initially funded by the Federal Ministry for Environment, Nature Conservation, and Nuclear Safety, later by the Federal Ministry for Economic Affairs and Energy; FKZ 0325314. The project results can be accessed on DIW Berlin's homepage: http://tinyurl.com/stores-publications.

3 See W.-P. Schill, "Systemintegration erneuerbarer Energien: Die Rolle von Speichern für die Energiewende," Vierteljahrshefte zur Wirtschaftsforschung 82, no. 3 (2013): 61–88. http://dx.doi.org/10.3790/vjh.82.3.61. Aside from the temporal and geographical balancing of electricity supply and demand, there is also a need for system services to ensure grid security, for example, providing reactive power to maintain voltage stability.

Figure 1

Electricity demand and supply from wind power and photovotaics for an overall renewable share of 80 percent

In gigawatts



Exemplary results of a simulation for two weeks, based on German load and feed-in data of 2013. The residual load ist the difference between load and the supply of fluctuating wind and solar power generators.

Source: Calculations by Zerrahn and Schill (2015), l.c.

Residual load is fluctuating heavily and may also become negative.

use of fluctuating renewable energy sources creates a growing need for flexibility in the electricity system. The challenge arises of how to satisfy the residual load—that is, the demand for electricity that remains after subtracting the power generated by wind energy and photovoltaics—using other energy sources. Figure 1 illustrates this with a stylized example of an electricity system using 80 percent renewables for electricity consumption, based on German feed-in and load time series for 2013.[4] Electricity generated from wind turbines is typically undergoing different fluctuations than that generated from photovoltaics. Within a short period of time, there may be temporary surpluses alternating with situations of high residual load.

In addition, short-term deviations in actual energy production as compared with the electricity market forecasts from the previous day need to be balanced out in real time. In practice, this is achieved by the provision and activation of control reserves. Geographical balancing is also required, because renewable power generation and electricity supply in Germany are generally distributed unevenly across the country.[5]

In principle, supply and demand must be balanced constantly in any electricity system—regardless of the share of renewables. In the context of the German energy transition, the need for flexibility is rising, although the precise trend will depend largely on the future power plant fleet and the size of the balancing area. One new aspect of flexibility raised by the energy transition is the uptake and later utilization of temporary power generation surpluses from renewable sources. However, in Germany, the relevance of such surpluses looks set to remain relatively minor for a long time to come, partly due to progress in expanding the grid.[6]

At the same time as flexibility requirements are rising, existing options for balancing are in decline. Most importantly, there is a drop in the capacities of dispatchable fossil power plants that have hitherto been able to produce electricity on demand and provide control reserves.

Power Storage and Other Flexibility Options

Various types of power storage facilities can help to meet the power system's flexibility requirements. The essential feature of a power storage facility is that it takes up electricity from the grid, or directly from a power generation plant, and releases it again later on, either back into the grid or directly to an electricity consumer. This process inevitably entails certain losses, so that less electricity is always fed back than was previously taken up. Pumped hydro storage technology has so far proved to be the most economical of the large-scale commercial electricity storage solutions.[7] These facilities make it possible to shift large volumes of energy over relatively long periods of time. Germany currently has pumped-storage facilities with a capacity of over 6 gigawatts (GW); a further 3 GW of capacity is also directly connected to the German transmission network, but comes from Luxembourg and Austria (see Table 1). At present, there are detailed plans for new pumped-storage facilities to the tune of around 5 GW in Germany. However, in recent years, no investment decisions have been taken on this matter.[8]

4 In the analysis, it was assumed for the sake of simplicity that electricity demand does not change. Furthermore, the hourly feed-in time series of German wind turbines and photovoltaics plants for 2013 were linearly scaled. No account was taken of effects that may contribute to a flattening of profiles in the future, especially changes to the geographical distribution and the technical configuration of the plants. As a result, the fluctuations in residual load may tend to be overestimated.

5 See J. Egerer et al., "Electricity Sector Data for Policy-Relevant Modeling: Data Documentation and Applications to the German and European Electricity Markets," DIW Data Documentation 72.

6 See W.-P. Schill, "Integration von Wind- und Solarenergie: flexibles Stromsystem verringert Überschüsse," DIW Wochenbericht, no. 34 (2013): 3–14.

7 This is particularly true for countries such as Germany with no substantial capacities of hydro reservoirs with natural inflow.

8 See the list of power plants issued by the German Association of Energy and Water Industries (BDEW, on April 7, 2014, and the Federal Network Agency (Bundesnetzagentur) power plant list (October 29, 2014). In Luxembourg and Austria, in contrast, decisions have been made regarding investment in pumped hydro storage in recent years.

Power storage facilities can be categorized in different ways:

- according to the energy form of the intermediate storage, for example, mechanical, electrochemical (batteries), or chemical storage facilities;
- according to the length of the discharge cycle (the relationship of energy storage capacity to power generation), with short-, medium-, and long-term storage facilities that can release their energy in seconds to minutes, hours, or days to weeks, respectively;
- according to purpose and network level, for example, central storage facilities in the transmission grid or decentralized facilities for local utilization.

On this basis, the currently prevailing pumped hydro storage technology may be characterized as mechanical, medium-term, grid storage.

Other Options for Increasing Flexibility

In addition to power storage facilities in the narrower sense (*power-to-power*), there are many other flexibility options on the production or demand side, many of which perform similar functions and can support a flexible balancing of supply and demand (see Table 2).[9] This means that the need for power storage facilities always tends to be lower than the flexibility requirements of the system as a whole.[10] The economic viability of power storage facilities in the narrow sense can therefore only be analyzed in relation to the competing flexibility options, which will now be briefly described.

Functional power storage (also *power-to-power*) acts in the electricity system as if electricity were first fed in and later fed out again. It includes the temporal displacement of electricity demand, the adjusted utilization of hydroelectric reservoirs (indirect hydro storage), and enhanced flexibility in the operation of biomass or combined heat and power (CHP) plants.

Further generation-side or demand-side (*X-to-power*) flexibility options aim for flexible electricity generation or exert a similar effect within the system. These include flexible conventional power plants, feeding in renewable energies on a more demand-oriented basis, and temporary load curtailment.

Table 1

Existing and planned pumped hydro storage facilities in the German transmission grid

Name	Federal state/country	Initial commercial operation	Nominal power in MW
Existing facilities			
PSW Vianden	Luxembourg	1962–1975, 2014	1291
Goldisthal	Thuringia	2003–2004	1052
Markersbach	Saxony	1980	1045
Wehr	Baden-Wuerttemberg	1975	910
Kopswerk I & II	Austria	1968, 2008	772
Waldeck 1 & 2	Hesse	1931, 1974	623
Rodundwerk I & II	Austria	1943, 2012	493
Hohenwarte 1 & 2	Thuringia	1959, 1966	378
Säckingen	Baden-Wuerttemberg	1966	360
KW Kühtai	Austria	1981	289
Lünerseewerk	Austria	1957	238
Erzhausen	Lower Saxony	1964	220
Witznau	Baden-Wuerttemberg	1943	220
PSW Langenprozelten	Bavaria	1974	164
Happurg	Bavaria	1958	160
Koepchenwerk	North Rhine-Westphalia	1989	153
Kraftwerk Waldshut	Baden-Wuerttemberg	1951	150
Pumpspeicherwerk Rönkhausen	North Rhine-Westphalia	1969	138
Geesthacht	Schleswig-Holstein	1958	119
Häusern	Baden-Wuerttemberg	1931	100
PSKW Reisach	Bavaria	1955	99
Leitzach 1 & 2	Bavaria	1960, 1983	99
Pumpspeicherkraftwerk Glems	Baden-Wuerttemberg	1964	90
Bleiloch	Thuringia	1932	80
Wendefurth	Saxony-Anhalt	1967	80
Rudolf-Fettweis-Werk (Forbach)	Baden-Wuerttemberg	1926	43
Niederwartha	Saxony	1957	40
PSKW Tanzmühle	Bavaria	1959	28
Other	-		2
Sum existing			**9435**
Planned projects			
Atdorf	Baden-Wuerttemberg	ns	1400
Schmalwasser	Thuringia	from 2025	1000
Jochberg/Walchensee	Bavaria	ns	700
Nethe/Höxter	North Rhine-Westphalia	from 2022	390
Jochenstein/Energiespeicher Riedl	Bavaria	2018	300
Heimbach	Rhineland-Palatinate	2019	300
Schweich	Rhineland-Palatinate	2019/20	300
Forbach (upgrade)	Baden-Wuerttemberg	ns	200
Blautal	Baden-Wuerttemberg	ns	60
Sum planned			**4650**

Planned projects according to BDEW. There are additional pumped hydro projects in Germany which are not included in the list.

Sources: Bundesnetzagentur List of Power Plants of 29.10.2014 and BDEW-Kraftwerksliste of 07.04.2014.

So far, no investment decisions have been made for the planned pumped hydro projects.

There are also options (*power-to-X*) that enable flexible utilization of electricity in other sectors, for exam-

9 See Schill, "Systemintegration erneuerbarer Energien," and especially Appendix 2 of the German Association of Energy and Water Industries, "Einschätzungen und Empfehlungen zu zukünftigen strommarktrelevanten Anforderungen an Flexibilität," BDEW discussion paper (Berlin: November 20, 2013).

10 See M. Sterner and I. Stadler, Energiespeicher: Bedarf, Technologien, Integration (Berlin: Springer, 2014).

Table 2

Power storage and other flexibility options

Category	Examples
Power storage in a narrow sense (power-to-power)	• Mechanical, electrochemical, chemical power storage
Functional power storage (power-to-power)	• Load shifting • Indirect hydro storage • Flexibilization of CHP and biomass
Other options on the supply- or demand-side (X-to-power)	• Flexible thermal generators • Adjusted feed-in of renewables • Temporary load curtailment
New flexible loads (power-to-X)	• Power-to-heat • Power-to-mobility • Power-to-gas (without reconversion)
Network-related measures	• Network expansion and optimization • Power electronics

Sources: Schill (2013a), l.c.

Aside from power storage in a strict sense, there are many other flexibility options.

ple, in heating or transportation[11] (*power-to-heat, power-to-mobility*) or the generation of chemical energy carriers (*power-to-gas* without reconversion). In the long term, these technologies are likely to gain ground, since they enable the indirect utilization of renewable energy sources and can therefore contribute to reducing greenhouse gas emissions in the areas of heating, transportation, or industry. The production of hydrogen using renewable electricity, in particular, may play an important role in the future.

Alongside these different forms of energy storage, there are various grid-related flexibility options, such as grid switching, network expansion and optimization, and the deployment of power electronics.

One further option for improving flexibility is to strengthen the European balancing area, in other words enhancing the opportunities for exchange with neighboring countries. Thus, for instance, the most cost-effective dispatchable power plants could be used to balance out short-term fluctuations in electricity supply across borders.

Power Storage Facilities Can Be Used for Multiple Applications

Power storage and other flexibility options can be deployed in a wide range of applications and market segments, for example, on the wholesale market and control reserve markets. There are also decentralized applications that are driven by optimization efforts on the microeconomic level under given institutional conditions, for instance, self-consumption of decentralized photovoltaic power generation.[12]

From the perspective of the electricity system as a whole, there are four important fields of application for power storage:

- Arbitrage: Shifting energy across time to take advantage of electricity price differentials on the wholesale market. This reduces system costs because electricity generation in high load periods with high variable costs can be partially replaced by generation in low load periods with lower variable costs.
- Ensuring capacity adequacy: Power storage facilities can contribute to covering peak loads, thus replacing other peak generation capacities, at least in part.
- Providing control reserves and other ancillary services (such as reactive power and black start capability).
- Managing network congestion: On the German electricity markets, this is carried out by means of redispatch measures.[13] In principle, power storage facilities can help reduce the need to expand transmission or distribution networks.

In short, based on the areas of application, power storage facilities can be assigned an arbitrage value, a capacity value, an ancillary service value, and a grid-related value.

Findings from Recent Studies on Storage Requirements

The question of future electricity storage requirements in Germany can basically only be answered in context. The required storage capacity depends not only on the areas of application under consideration but also on the conventional and renewable power plant fleet, the size of the interconnection, the availability of other flexibil-

11 On this point, see also W.-P. Schill, C. Gerbaulet, and P. Kasten, "Elektromobilität in Deutschland: CO_2-Bilanz hängt vom Ladestrom ab," DIW Wochenbericht, no. 10 (2015): 207-215. An english version appears in the DIW Economic Bulletin no. 17 (2015). See also W.-P. Schill, C. Gerbaulet, "Power System Impacts of Electric Vehicles in Germany: Charging with Coal or Renewables?," DIW Discussion Papers no. 1442 (2015).

12 There are also other niche applications, for example uninterruptible power supply or off-grid uses. This report, however, focuses on storage applications in the transmission grid.

13 See J. Egerer et al., " Energiewende und Strommarktdesign: zwei Preiszonen für Deutschland sind keine Lösung," DIW Wochenbericht, no. 9 (2015).

ity options, and not least, the storage costs. The following section outlines the findings of three recent studies conducted for Germany. Here, storage requirement is generally defined in terms of an economically viable storage capacity in the context of other flexibility options.

A study on storage by the Association for Electrical, Electronic & Information Technologies (VDE)[14] examines the demand for short- and long-term storage with various shares of renewables using a power plant dispatch model.[15] While no additional storage capacity is required in Germany for a renewable energy share of 40 percent, 14 GW short- and 18 GW long-term storage facilities would be advantageous for an 80-percent share; if the share rises to 100 percent, these values increase sharply to 36 GW short- and 68 GW long-term storage. This is, however, abstracted from many of the flexibility options mentioned above, in particular from European exchange of electricity and demand-side options. In this respect, the storage requirement is likely to be overestimated.

In the *Roadmap Speicher* (Storage Roadmap) study,[16] medium- and long-term power storage requirements are simulated with multi-stage dispatch models in which the European power plant capacities are also partially optimized in the long run. No additional power storage is required beyond assumed stocks of pumped storage[17] for renewable shares of less than 70 percent. An 88-percent share requires an additional storage requirement of between 0 and around 20 GW in Germany, depending on assumed availability of solar thermal electricity imports, demand-side management, and other flexibility options. This will only require short-term storage facilities. In contrast to the VDE study, substantial European balancing is taken into account with the assumed share of renewable energies being lower in neighboring countries than in Germany. Furthermore, it is assumed that electricity demand is largely flexible.

A study which is methodologically related to the "Storage Roadmap" and commissioned by Agora Energiewende[18] comes to similar conclusions. It finds that a renewable energy share of up to 60 percent requires no additional stored electricity, in principle. A small expansion of long-term storage is only required for optimistic storage cost developments and lower flexibility in the remainder of the system. Only if the share of renewable energies reaches 90 percent, substantial capacities of additional power storage facilities are required. Additional 7 GW of short-term and 16 GW of long-term storage lead to the largest cost savings.

The studies mentioned above largely focus on the arbitrage value of power storage, while other system benefits of storage are not included in the VDE study at all and only to some extent in the other two studies. This could lead to a systematic underestimation of the system value of power storage. The joint conclusion of the above studies is that, from a system perspective, no additional expansion of power storage is needed in the short to medium term.[19] The long-term simulations, however, show a rather mixed picture which is particularly dependent on the availability of other flexibility options.

Sensitivity Calculations Show Storage Requirements Can Increase Significantly in the Long Run

A power plant dispatch and investment model was developed at DIW Berlin as part of the StoRES project and used to analyze long-run power storage requirements (see box). All power generation capacities are defined as decision variables in the model with a time horizon around 2050. In addition to the wholesale sector, the provision and activation of control reserves are also taken into account. This allows depicting not only the arbitrage value of power storage but also its capacity value and contribution to the provision of reserves.

Baseline assumptions (see box) lead to a power mix largely based on photovoltaics and onshore and offshore wind power. When minimum shares of renewable energy increase, the share of gas-fired power plants in electricity consumption decreases while, at the same time, power storage becomes more important (see Figure 2). While these energy shares vary only slightly, overall installed

14 ETG-Task Force Energiespeicherung, Energiespeicher für die Energiewende. Speicherungsbedarf und Auswirkungen auf das Übertragungsnetz für Szenarien bis 2050, (Frankfurt am Main: Energietechnische Gesellschaft im VDE (ETG), June 2012).

15 A comparable model framework was used for a study of the maximum storage requirement for taking up renewable surpluses in Germany. See W.-P. Schill, "Residual load, renewable surplus generation and storage requirements in Germany," Energy Policy 73 (2014): 65-79, http://dx.doi.org/10.1016/j.enpol.2014.05.032

16 C. Pape et al., Roadmap Speicher. Bestimmung des Speicherbedarfs in Deutschland im europäischen Kontext und Ableitung von technisch-ökonomischen sowie rechtlichen Handlungsempfehlungen für die Speicherförderung, final report, (Fraunhofer IWES, IAEW, Stiftung Umweltenergierecht, November 2014).

17 In the scenarios with shares of renewable energy below 70 percent, an existing pumped hydro storage capacity of 8.3 GW is assumed in Germany; in the 88-percent scenario, it is 8.9 GW. Additionally, current pumped storage in Luxembourg at Vianden with its capacity of 1.3 GW has been taken into account in all scenarios.

18 Agora Energiewende, Stromspeicher in der Energiewende. Untersuchung zum Bedarf an neuen Stromspeichern in Deutschland für den Erzeugungsausgleich, Systemdienstleistungen und im Verteilnetz (September 2014).

19 A model analysis that examines the interactions of investments in power storage, gas-fired power plants, and grid expansion in Germany also comes to this conclusion. See J. Egerer and W.-P. Schill, "Power System Transformation toward Renewables: Investment Scenarios for Germany," Economics of Energy and Environmental Policy 3 (2014): 2, 29-43, http://dx.doi.org/10.5547/2160-5890.3.2.jege

Box

A Power Plant Dispatch and Investment Model for Studying Long-Run Storage Needs

A new power plant dispatch and investment model was developed at DIW Berlin as part of the StoRES project.[1] The decision variables of the model not only include the dispatch of various technologies but also the respective installed capacities. The model follows a greenfield approach which abstracts from existing capacities and identifies an optimized overall system. The model consequently adopts a very long-term perspective around 2050. Power exchange with other countries is not explicitly represented in this stylized model framework.

The objective function is to minimize the investment, fixed, and variable costs of renewable and conventional technologies. To achieve this, specific annualized investment costs are assumed for aggregated technologies. The variable generation costs of conventional technologies are calculated from fuel costs, CO_2 costs, and technical parameters of typical plants.

The model has an hourly resolution and is solved for an entire year. In every hour, the amount of electricity generated must meet demand. Other constraints relate to the use of storage and demand-side measures for temporarily shifting load and generation, and providing control reserves dependent on the installed capacities of wind turbines and photovoltaic systems. The model sets minimum shares of renewables between 70 and 100 percent. Consequently, model results represent the minimum cost of the power plant fleet and the respective dispatch in a future electricity system with very high shares of renewable energy.

1 A. Zerrahn and W.-P. Schill, "A greenfield model to evaluate long-run power storage requirements for high shares of renewables," DIW Discussion Papers, no. 1457 (2015, forthcoming).

The basic version of the model contains three different power storage technologies that differ according to their specific investments in energy storage and power generation capacity as well as roundtrip-efficiency: short-term storage based on lithium-ion batteries, medium-term storage similar to pumped hydro storage, and long-term storage similar to power-to-hydrogen with subsequent reconversion. All technical and economical storage parameters are taken from future expectations of the Storage Roadmap study.[2] Several demand-side management technologies are considered to be additional flexibility options, including load shifting and load curtailment.

The data basis of the model is loosely calibrated on the parameters of the German electricity system: the hourly feed-in profiles of load, wind power, and photovoltaics are based on time series from the year 2013. Some potential restrictions are also assumed: the expansion of offshore wind energy is limited to 32 GW, the energy storage capacity of pumped storage to 300 GWh, and the annually available energy from biomass for power generation is 60 TWh. In demand-side management terms, the potential for load curtailment is limited to a good 10 GW and to a good 7 GW for load shifting. Investments in nuclear energy are not possible. A CO_2 price of 100 euros per ton is assumed.

Several variations to the model's baseline assumptions are examined in sensitivity calculations, relating, for instance, to the costs of different storage types, the provision of reserves, the potential of demand flexibilization, the development of offshore wind energy, and biomass capacity.

2 Pape et al., Roadmap Speicher.

capacities grow rapidly in the scenarios with shares of 90 percent and 100 percent. For instance, the power storage capacity will increase from 10 GW in the 70-percent scenario to almost 22 GW in the 90-percent scenario and 34 GW in the 100-percent scenario (see Figure 3). Therefore, to achieve full electricity supply through renewable energy in the examined scenario, more than three times the storage capacity would be required than is currently available in pumped storage for the German transmission grid.

In the 90- and 100-percent scenarios, medium-term storage makes up by far the largest share. Long-term storage is only required with a fully renewable power supply and, even then, only to a small degree.[20] If renewable energy is assumed to be the only source of power, flexibility requirements are not fully met by power storage in the model but also by other options, in particular by a disproportionate expansion of wind power and photovoltaic systems in combination with temporary generation curtailment, demand-side measures, and a

20 Under the alternative assumption that no biomass is available for power generation, full energy supply through renewables would require a very strong increase in the long-term storage capacity to around 30 GW.

much-increased power rating of plants producing electricity from biomass.[21]

Sensitivity calculations allow the effects of different assumptions on the storage requirements to be illustrated in a graph (see Figure 4). For example, if no biomass can be used, power storage requirements would increase significantly. The same applies if offshore wind energy could not be used because this would then require an increased expansion of more volatile electricity generation from photovoltaics. If demand-side flexibility options cannot be developed as assumed in the baseline model, the storage requirement also increases significantly. Conversely, a doubling of the demand-side flexibility potential leads to a reduction in power storage requirements, even if power storage and demand-side measures are not perfect substitutes. If the provision of control reserves is neglected, demand for short-term storage falls but rises sharply when demand for reserves doubles. Accordingly, models that abstract from reserves underestimate, in particular, short-term storage requirements. If specific investment costs of short- or long-term storage halve, as assumed, then the effects on short-term storage are very clear, but not those on long-term storage which is even then inferior to other flexibility options in terms of cost. The findings of the model indicate, therefore, that the evaluation of the future power storage requirement essentially depends on various factors whose development from a present-day perspective are subject to significant uncertainties.

In view of the German government's ambitious climate targets and the major challenges outside the electricity sector, it may be necessary to generate very high amounts of electricity from renewable sources faster than previously planned. In this case, investments in power storage could be required significantly earlier.

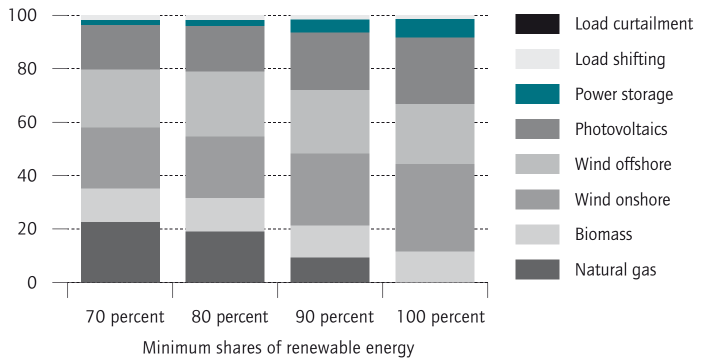
Political Support for Power Storage

Policy-makers can influence the development and application of energy storage in different ways. In particular, this includes promoting research and development to improve efficiency and environmental compatibility and to lower costs, thereby bringing to market storage technologies that are not yet commercially available. In addition, by creating the appropriate environment, fair competition can be encouraged between power storage and other flexibility options in various areas of application. Where relevant, financial support can also be provided for the testing, demonstration, and commercialization of storage technologies.

Figure 2

Power supply in the baseline scenario of the long-term simulation

Shares in percent



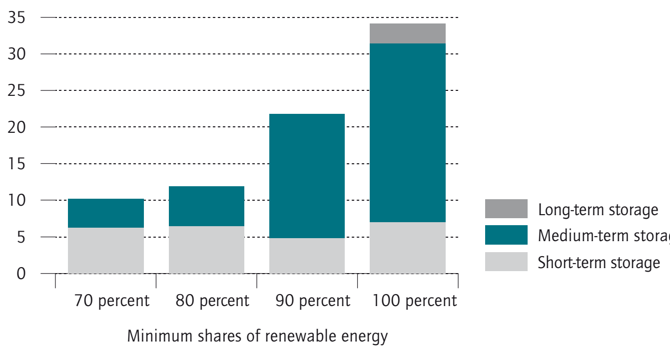
Source: Zerrahn und Schill (2015), l.c.

Wind power and PV have major shares in the long-term simulation.

Figure 3

Power storage capacities in the baseline scenario of the long-term simulation

In gigawatts



Source: Zerrahn und Schill (2015), l.c.

If the overall share of renewables increases from 70 to 90 percent, storage requirements more than triple.

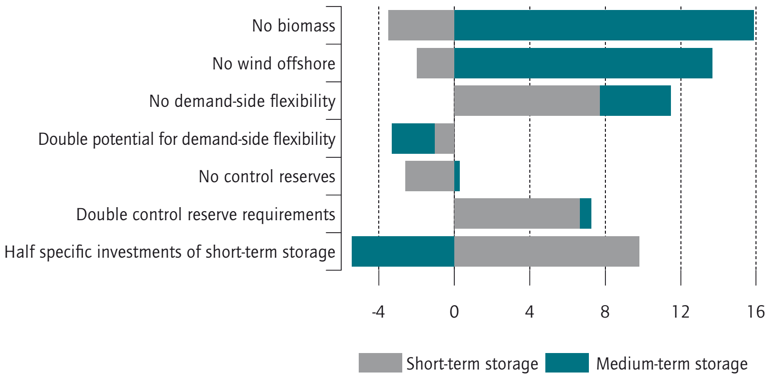
Central Government Strengthens Its Commitment to Research and Development

At the federal level, the research, development, and demonstration of energy storage technologies have been given increasing support in recent years. Since 2005, some

21 Based on a given biomass budget, this would lead to a significant reduction in the average utilization of these plants. Incentives set by a flexibility premium in Germany's Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) have a similar effect. See K. Rohrig, J. Diekmann et al., Flexible Stromproduktion aus Biogas und Biomethan: Die Einführung einer Kapazitätskomponente als Förderinstrument. Report on the project, Weiterentwicklung und wissenschaftliche Begleitung der Umsetzung des Integrations-Bonus nach § 64 Abs. 1.6 EEG commissioned by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Figure 4

Power storage capacities in different sensitivity analyses
Changes compared to baseline in gigawatts



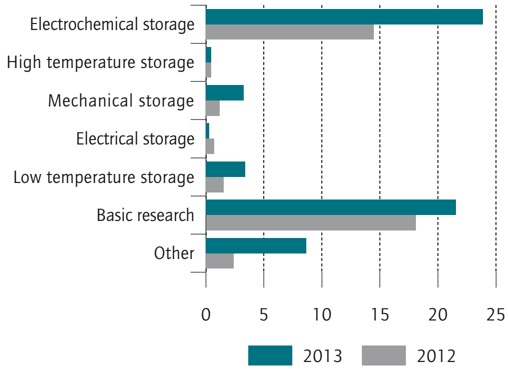
The graph shows the changes in storage capacities compared to the baseline for an overall renewable share of 80 percent.

Source: Zerrahn und Schill (2015) l.c.

Storage requirements strongly depend on the development of several factors.

Figure 5

Outflow of funds of federal research support for energy storage projects
In million euro



Basic research including other programs.
Source: BMWi (2014), l.c.

Research funding has increased in 2013, in particular for battery storage.

380 individual projects on various storage technologies have been supported as part of research funding from several German ministries, including almost 200 in the field of power storage.[22] The total support amounted to almost 280 million euros (a good 170 of which was for power storage), just six percent of all energy-related research projects funded by the German government in this period.

More recently, research funding for storage has increased significantly. The outflow of funds of the central government's project funding increased to 61 million euros in 2013, compared to 39 million euros in the previous year.[23] In 2013, this represented almost eight percent of the total outflow of funds for energy research. The key focus here was on electrochemical storage devices (batteries) and fundamental research (see Figure 5). In addition, central government project funding for fuel cells and hydrogen, a field of technology that overlaps with long-term power storage, rose in 2013 to just under 25 million euros, compared to around 19 million euros in the previous year.

Funding for storage research was increased by the *Forschungsinitiative Energiespeicher* (*Energy Storage Funding Initiative*) established in 2011, which bundled the federal government's activities on storage research.[24] It had total funding of 200 million euros which was made available in the first phase up until 2014. Funding was provided for developing power storage devices, material and thermal energy storage, and overriding storage research topics.

Allow Competition among Flexibility Options

Policy-makers can ensure that power storage and other flexibility options can compete on a level playing field by providing the appropriate framework. In particular, this includes non-discriminatory access to all relevant segments of the electricity market and, where appropriate, an adapted definition of market products.

For example, power storage facilities benefit from volatile electricity prices in the wholesale market. Moderating price volatility or capping peak prices, through capacity mechanisms, for example, may adversely affect the potential applications of energy storage. If capacity mechanisms were to be introduced, appropriate prequalification would also be needed to ensure that electricity storage and other flexibility options are not dis-

22 Information is based on a recent analysis of the central government's funding catalog from January 2015, http://foerderportal.bund.de/foekat, last accessed on December 1, 2015. Projects starting between early 2005 and late 2014 were analyzed.

23 Federal Ministry for Economic Affairs and Energy, Bundesbericht Energieforschung 2014. Forschungsförderung für die Energiewende (Berlin: July, 2014).

24 http://forschung-energiespeicher.info/en

Table 3

Approvals of funding for PV-battery storage

	2013 (since May)		2014		Sum	
	Number of supported projects	Loan commitments in million Euro	Number of supported projects	Loan commitments in million Euro	Number of supported projects	Loan commitments in million Euro
Supplementary storage for existing PV installations	201	2	690	7	891	9
New PV installations including storage	2529	43	4871	82	7400	125
Total	2730	45	5561	89	8291	134

Source: KfW-Förderreport 2014 of February 2015.

Overall, 8291 PV-battery storage systems were supported until the end of 2014.

advantaged.[25] In practice, this is likely to be a major challenge. Not least, bid sizes and tender and delivery periods in the reserve market should be designed in a way that storage- or demand-side flexibility options are not adversely affected.[26]

The regulatory framework can also be adapted to allow a fair competition of various flexibility options, for instance, in terms of grid connection, network charges, surcharges in accordance with the Renewable Energy Sources Act, or electricity tax. The government has enacted selective regulations for individual storage technologies. For example, new power storage technologies are exempt from paying network charges for a period of 20 years.[27] Electricity and gas grid tariff exemptions were adopted for power-to-gas technologies, and pumped storage was exempt from electricity tax.[28] Overall, however, the current legal framework for flexibility options is still considered to be inconsistent, and there are distortions in favor of individual power storage technologies.[29]

Financial Support for Photovoltaic Battery Storage

In addition to promoting research and development, and creating a suitable framework, policy-makers can in principle promote the market introduction of storage devices in certain areas of application. As part of a limited funding program from 2013 to 2015, the German government is currently supporting the installation of decentralized battery storage in connection with new photovoltaic systems or those established since the beginning of 2013. A low-interest loan and repayment bonus equal to 30 percent of the eligible costs of the battery storage system is granted as part of the program 275 funded by the German promotional bank *KfW*.[30] A maximum subsidy rate of 600 or 660 euros per kilowatt (peak) for a 5-kWphotovoltaic system, for example, results in a grant of some 3,000 euros. Certain eligibility criteria apply, such as a permanent restriction of grid feed-in to 60 percent of the photovoltaic system's output. This should encourage, at least partially, grid-oriented operation of battery storage.

According to current information from the *KfW*, 8,291 systems were granted loans worth 134 million euros from May 2013 to the end of 2014 (see Table 3). However, the repayment grants only account for a portion of the loan commitments, so the actual subsidy volume is in fact lower. The proportion of all photovoltaic systems commissioned in Germany in 2013 and 2014 was just under five percent.[31] Assuming that typical battery systems have storage capacities of around five to ten kW,

25 See M. Nicolosi, Arbeitspaket Optimierung des Strommarktdesigns, study commissioned by the Federal Ministry for Economic Affairs and Energy, final report dated July 2, 2014.

26 See, in particular, chapter 4.1 of Federal Ministry for Economic Affairs and Energy, Ein Strommarkt für die Energiewende, discussion paper by the Federal Ministry for Economic Affairs and Energy (Green Paper) (Berlin: October 2014).

27 See Section 118 of the German energy act (Energiewirtschaftsgesetz, EnWG) as amended on July 21, 2014. The exemption applies to new storage facilities constructed after December 31, 2008 and commissioned within 15 years of August 4, 2011, and also to existing pumped storage facilities if pump or turbine power rating was increased by at least 7.5 percent or if the energy storage capacity was increased by at least five percent.

28 See section 12 of the regulation for implementing electricity tax legislation (Verordnung zur Durchführung des Stromsteuergesetzes, StromStV), last amended on July 24, 2013.

29 See, in particular, chapter 8 in Pape et al., Roadmap Speicher.

30 See KfW, Merkblatt Erneuerbare Energien: KfW-Programm Erneuerbare Energien "Speicher", dated January, 2015.

31 According to the Federal Network Agency, 184,179 PV systems were commissioned in 2013 and 2014 with a power output of up to 30 kW (system registrations). In addition, there are PV-connected power storage installations without KfW funding.

this results in a total output of subsidized battery storage in the order of 0.1 GW, which is still very low compared to installed pumped storage (see Table 1).

A decision still has to be made concerning possible continuation of funding for photovoltaic battery storage. It requires a detailed assessment of costs and benefits. Costs associated with so far still rather high prices for battery storage are juxtaposed with possible experiences and technological learning in installing and operating decentralized battery storage, in particular, with regard to grid-oriented storage operation. The experience gained in the storage funding program should therefore be carefully evaluated.[32]

Conclusion and Policy Implications

The energy transition will lead to an increasing need for flexibility in the electricity system. In principle, different types of power storage can make contributions to this in various fields of application. There are also a variety of other generation-, demand-, and network-side flexibility options that are partly in competition with power storage.

The question of future power storage requirements is highly dependent on context. Assuming that other generation- or demand-side flexibility options can at least be partly developed, various studies and own calculations have come to the conclusion that the expansion of power storage in the short and medium term will not pose a barrier for the energy transition. This means that the further expansion of electricity generation from fluctuating renewables is possible without any major increase in power storage for the time being. In the longer term, however, a variety of uncertainties give a mixed picture of storage requirements. Basically, many model analyses tend to underestimate the overall system benefits of power storage when all the relevant value contributions are not taken into account for the overall system.

A recent analysis by DIW Berlin not only takes into account the arbitrage value of storage, but also its contribution to providing control reserves and firm generation capacity. It comes to the conclusion that power storage requirements might increase significantly with very high shares of renewable energy sources. In addition, storage requirements would continue to increase if, for example, the relatively even power generation from offshore wind turbines or the potentials of demand flexibility could not be developed.

There are still fundamental uncertainties about the future development of costs and potentials of various demand-side or generation-side flexibility options. If options such as flexible power generation from natural gas and biomass, flexibilization on the demand side, or international contributions to integrating renewable energy develop less favorably than frequently assumed, additional power storage will be required and prove to be economically advantageous in the long term. Furthermore, the future role of power storage significantly depends on possible cost reductions. Therefore, support for power storage is a useful element in a preventive policy to safeguard the energy transition.

In view of the government's ambitious climate targets and major challenges in other sectors, it may also be necessary to achieve very high shares of renewables in the electricity sector faster than previously planned. Investments in power storage could, therefore, be required significantly earlier than was simulated in current model calculations.

Against this background, policy-makers should primarily continue to work toward technology advances and cost reductions in power storage through broad-based research funding and, at the same time, allow fair competition of flexibility options in various areas of application.

32 A scientific measurement and evaluation program on solar power storage is currently being conducted by RWTH Aachen and will be completed in April 2016.

Wolf-Peter Schill is Research Associate in the Department Energy, Transportation, Environment at DIW Berlin | wschill@diw.de

Jochen Diekmann is Deputy Head of the Department Energy, Transportation, Environment at DIW Berlin | jdiekmann@diw.de

Alexander Zerrahn is Doctoral Student in the Department Energy, Transportation, Environment at DIW Berlin | azerrahn@diw.de

JEL: Q42, Q47, Q48

Keywords: Power storage; renewable energy; Germany

Dr. Wolf-Peter Schill, Research Associate in the Department of Energy, Transportation, Environment at DIW Berlin

SEVEN QUESTIONS TO WOLF-PETER SCHILL

»Continued and Broad-Based Support for Research and Development of Power Storage Needed«

1. Dr. Schill, how important is power storage for Germany's energy transition? In the course of the energy transition, fluctuating renewable energy is expanded significantly. The power generation capacities of renewables vary according to the weather, time of day, and season. Electricity storage facilities can help offset these temporary fluctuations and bring power generation in line with demand. They can also compensate for deviations from generation forecasts within a very short period of time.

2. To what extent are we already dependent on power storage? We currently have a good six gigawatts of installed pumped hydro storage capacity in Germany and an additional three gigawatts abroad which are directly connected to Germany's transmission grid. At present, there is no shortage of storage and, also in the immediate future, power storage facilities will not create any congestion for the energy transition. Obviously, however, power storage will become increasingly important if we continue to expand the share of electricity generated from renewables and move toward complete reliance on renewable energy sources.

3. From what stage of the expansion of renewables does creating additional storage capacity become unavoidable? This cannot really be answered in general terms. Storage requirements heavily depend on the context. They are not only contingent on the share of renewable energy but also on the cost development of the various types of storage. Requirements also depend on the overall system, particularly the availability and cost of other flexibility options.

4. What other options are available to increase the flexibility of the power system? There are a variety of other flexibility options which can perform the same or at least a very similar function to power storage. These include shifting electric load to certain hours of the day, more flexible power generation using biomass or natural gas, for example, and also flexible electricity consumption in other sectors. The latter is also known as "power-to-X," which means that electricity flows from the grid to other areas of use, such as the transport or heating sectors.

5. Which of these flexibility options are the most efficient? A cost-effective system will always provide different options. A number of studies strongly suggest that a wider interconnection enabling European exchange of electricity is a very cost-effective option. This option essentially has two effects. First, it results in a blending of demand and feed-in profiles of renewable energy sources in the different countries, creating smoother profiles on the whole. Second, it can be linked in with other existing flexibility options such as hydro storage in the Alps region. International balancing of electricity would definitely play an important role in achieving a cost-effective mix but we should not rely exclusively on this option.

6. What are the different types of power storage and which of these are worth considering for Germany? Germany has already developed substantial capacity of pumped hydro storage technology, which has been established for many years, and could further expand this capacity in the future. To meet the demand for short-term storage, different battery technologies could play an important role. For long-term storage, power-to-gas with subsequent reconversion might prove to be a promising option.

7. How should policy-makers pave the way for future power storage? First, policies should pave the way for fair competition with regard to power storage and other flexibility options. This includes non-discriminatory access to all relevant segments of the electricity market, particularly operating reserves. Second, we need continued and broad-based support for research, development and demonstration of different storage technologies.

Interview by Erich Wittenberg