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Current Issues
Natural resources

State-of-the-art electricity storage systems

Indispensable elements of the energy revolution

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An ambitious shift in energy policy, such as that of the German government and which other countries are aiming to emulate, poses great challenges. One Herculean task is integrating those renewable sources of electricity generation which are experiencing dynamic growth but are also subject to relatively strong fluctuations.

The volatility of the increasing volumes of solar and wind energy needs to be evened out and matched to consumption in order for Germany to enjoy a stable power supply and avoid blackouts. Storing electrical energy is a proven means of absorbing any immediate surplus power and then making it available when required.

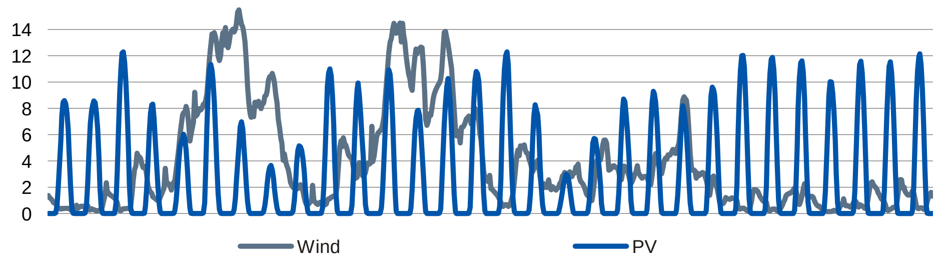
By 2025, the requirement for short-term power storage could well double at the very least and increase still further thereafter. The end of production from ageing fossil-fuel power stations and the abandonment of nuclear energy require new capacity available on demand (in addition to the options of more imports, renewables and greater capacity utilisation) in order to avoid bottlenecks. Pumped and compressed air storage systems and storage power stations can offer short-term storage.

By 2040 at the latest, it will be regularly necessary to store 40 TWh in order to absorb the surpluses which will arise. The electricity will then need to be stored for several weeks and months. In the next two decades alone, the capital investment required for new energy storage systems in Germany will total around EUR 30 bn.

Hydrogen and methane storage systems will need to be developed further so that the energy revolution can remain affordable and be implemented with assurance. Alternative or additional adjustment strategies, such as accelerating and expanding the integration of the European electricity grids, must also be driven forward.

Fluctuations in wind and solar-generated electricity

Hourly feed-in values (GW), Germany, September 2011



Source: ENTSO-E

State-of-the-art electricity storage systems

1. Refocusing the electricity industry meets with obstacles

This study will analyse the extent to which the growing volume of regenerative electricity (see chart 2) and thus the disparity between power production and power consumption can lead to the loss of the electricity produced and jeopardise an assured electricity supply (without this being due to undersupply or any failures in the grid). First, the structure and size of the problem will be outlined; and then the requirements for solutions and their possible market potential will be deduced.

The basic question to be examined is whether modern electricity storage systems are capable of matching the dynamic structural change to energy supplies. Various technical approaches, including pumped storage systems and pumped storage hydropower stations, compressed air energy storage, and hydrogen and methane storage[1] will be discussed and evaluated against efficiency and cost criteria.

The energy revolution is in full swing

Germany's abandonment of nuclear power in 2011 has attracted a relatively broad social consensus. In other countries, too, adding further nuclear capacity has become more difficult to achieve politically following the Fukushima disaster. At the same time, both in Germany and elsewhere, the continuing political will to reduce climate-damaging CO_2 emissions is clearly discernible. Against this background, it is helpful that technical advances are enabling new technologies based on wind power and photovoltaics (PV) to gradually generate electricity at ever lower costs. In contrast, it is becoming increasingly difficult, and thus likely to be increasingly expensive, to extract the remaining finite reserves of fossil energy sources such as oil and coal. In future, the biggest obstacle renewable energies have to surmount, namely achieving price levels which can compete with conventionally generated power, will gradually become less relevant. The latest wind farms on the North Sea coast are already generating power at domestic electricity prices; although the prices on the energy exchange markets are noticeably lower on average.

The success of renewables creates a new problem

Generating power from renewable energy sources is subject to extreme fluctuations and cannot be controlled since the period during which power is generated (when the wind is blowing or the sun shining) only coincides by chance with power consumption. Already, today, not all the green energy generated can be fed into the grid all the time.

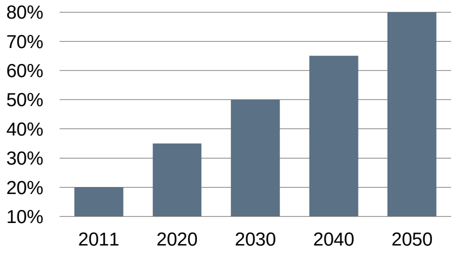
Electricity generation from PV systems and wind power changes over the year with a certain regularity. Also, in the case of PV, relatively uniform changes can be observed during the day. In addition, particularly as regards light and strong winds, stochastic fluctuations occur over periods of between several days and weeks at a time. Power consumption, too, follows a characteristic pattern, changing over the year, week or day and also fluctuating due to other factors which occur less regularly (see charts 3-5).

Several countries are abandoning nuclear energy 1

A formal decision to abandon nuclear energy has been taken in several countries, e.g. in Germany by 2020, in Belgium by 2025 and in Switzerland by 2034. Since the Fukushima accident, the policy has been questioned in many countries with a dominant nuclear energy sector. France's socialists intend to remove 24 nuclear plants from the network and reduce the part played by nuclear energy from 78 to 50 per cent within ten years. The Japanese prime minister announced his country's abandonment in 2011. A referendum in Italy in 2011 rejected the renaissance of nuclear energy.

Germany: renewables more important 2

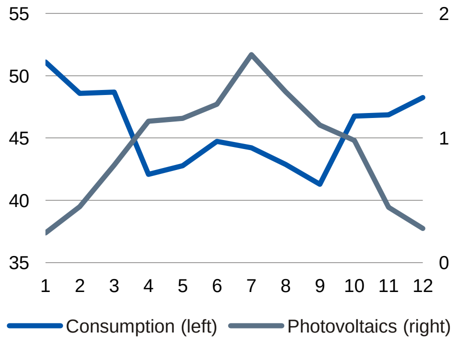
The renewables' share of gross electricity generation (%)



Source: Federal German government

PV electricity generation over the year vs. consumption 3

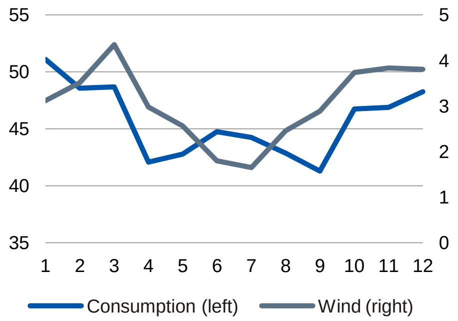
Monthly data 2010, Germany (TWh)



Source: ENTSO-E

Wind electricity generation over the year vs. consumption 4

Monthly data 2010, Germany (TWh)

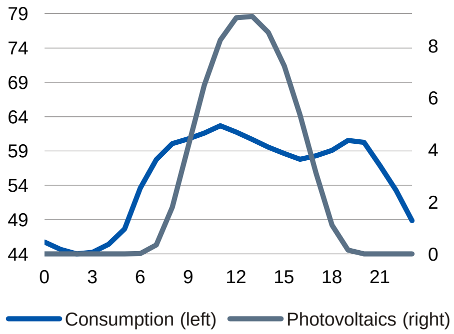


Source: ENTSO-E

[1] We are limiting discussion of the topic to static, central electricity storage systems linked (directly or indirectly) to the grid. This excludes portable and small-size applications (e.g. batteries, electromobility), primarily designed for independent use or as part of standalone systems. Also excluded from the analysis are technologies designed for extremely brief storage periods (e.g. capacitors) and applications mainly designed for storing types of energy other than electricity (such as heat storage).

Fluctuations in consumption and PV electricity over the day 5

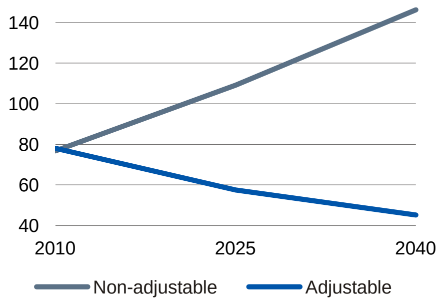
Daily averages (GW), Germany, September 2011



Sources: EEG/KWK-G, ENTSO-E

Electricity generation more difficult to manage in future 6

The trend in net power station capacities, 2010, 2025 and 2040 (GW)



Source: DB Research

Important capacity terminology 7

Must-run capacity

The minimum capacity utilisation of nuclear and lignite-fired basic load power stations plus run-of-river power. For safety, technical or commercial reasons, capacity cannot drop below this level nor be altered, except for emergencies.

Residual or adjustable capacity

The output from controllable peak load power stations (storage power plants and adjustable run-of-river power, biomass, gas, oil) and from medium load power stations (coal) plus the variable proportion of the capacity of basic load power stations (difference between maximum and minimum capacity utilisation).

Fluctuating capacity

The fluctuating, non-controllable output from wind power and PV systems.

Since the electricity grid does not store electricity, at any given time exactly the same volume needs to produced or fed in as is being taken out, otherwise the grid will collapse. Load management – actively balancing the power being fed in with the power being consumed – is essential to prevent this.

New solutions are important but will not be enough

The most recent approaches include the use of smart grids and smart metering, whereby consumers can help ensure that consumption by their domestic appliances, air conditioning and electric heating systems matches the volume of electricity generated. We have assumed that only a small proportion of consumption can be matched to power generation because of the limited number of appliances which can be used flexibly and because the concept offers little financial incentive at the domestic level.[2] We reckon that, by 2025, 6 per cent of power consumption could be adjusted variably, and 10 per cent by 2040. Essentially, consumption would be cut back during power bottlenecks and increased if it was likely that a surplus would be generated.

Further expansion of transmission grids (especially the construction of a trans-national supergrid) would both ease pressure on the grid and tone down region-al renewable energy fluctuations. However, the particularly sluggish expansion of national grids is matched by even slower progress at the European level.

The construction of offshore wind farms and taller wind turbines (new build, repowering) will also permit electricity to be fed into the grid more uniformly by exploiting the more constant wind conditions. We calculate that the base load capacity of wind power available at any given moment will increase from 0.3 per cent of the installed capacity in Germany today to 1 per cent by 2025 and to 3 per cent by 2040. Consequently, the potential for smoothing national fluctuations is limited.

Greater individual consumption of solar power is another way of relieving the pressure on grids at the lower end of the scale. In 2010, direct individual con-sumption from those PV systems which had taken advantage of the German Renewable Energy Sources Act represented 0.4 per cent of the total PV electricity generated. It would appear possible to increase this to 20 per cent by 2025 and to 35 per cent by 2040.[3] However, demand for power cannot to be timed so as to coincide with when it is generated.

A different power station fleet offers other options

In the past, electricity generation was adjusted to consumption (load following) by using flexible power stations. Until now, these stations have provided a large proportion of the electricity by means of variably produced residual load. Very flexible power plants also compensated for unexpected fluctuations in demand or power station outages by providing an adjustable output or by making other system services available.[4] Chart 6, opposite, illustrates the development of adjustable and non-adjustable capacities implied by our basic scenario.[5]

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[2] Cf. Auer, Josef and Stefan Heng (2011). Smart grids: Energy rethink requires intelligent electricity networks. Deutsche Bank Research. E-conomics 84. Frankfurt am Main.

[3] Federal Network Agency (2011). Renewable Energy Sources Act statistical report 2009. Bonn; Leipziger Institut für Energie GmbH (2011). Annual forecast for 2012 of total German electricity generation from regenerative power stations. Leipzig.

[4] Safety-related, technical and economic factors (e.g. load change speed and efficiency loss) determine the plant's suitability to deliver adjustable power, to run at partial load or to be switched off as a cold reserve. Lignite-fired and nuclear power stations can also be operated in load following mode to a limited extent.

[5] This trend is less disturbing than the diagram suggests since the PV feed-in peaks coincide with peaks in consumption. Also, 100 per cent capacity utilisation of all wind turbines installed is never

Important system services 8

System services such as voltage and frequency preservation and the provision of reactive power and minute reserves are essential for disruption-free power supply. These services are regularly traded in the market as feed-in and draw-off capacities available on demand.

Power station capacities 9

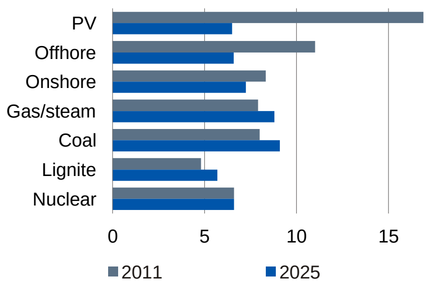
Without building any new conventional power stations after 2014 (GW)

	2010	2025	2040
Wind	27,3	57,1	68
PV	17,0	39,5	67
Biomass	4,8	10,0	20
Hydropower	4,7	5,2	6
Gas	25,7	16,2	12
Coal	28,0	23,5	9
Lignite	20,3	14,0	10
Nuclear power	20,5	0,0	0
Oil, miscellaneous	6,5	1,2	0

Sources: BDEW, Federal Network Agency, DB Research

Electricity generation costs 10

Germany (cents/kWh)



Sources: BDEW, DIW

Important assumptions 11

Assumptions for conventional energy are based on EEX spot prices for November 2011. We have assumed emission allowances in the range of EUR 10 (2011) and EUR 20 (2025), USD 110/t of coal in 2011 and USD 125/t for 2025, 2.3 cts/kWh for gas in 2011 and 2.6 cts/kWh in 2025. Compared with others, these assumptions are relatively conservative.

The assumptions for wind from North German coast onshore sites (on average 1,040 kWh/p.a./qm, cost degression: 1 per cent p.a.) and from offshore sites in 20 m of water and 20 km out to sea (cost degression: 5 per cent p.a., from 2015). As for PV, we have assumed 92 cts/Wp (average Chinese supplier in October 2011), system costs of 50 cts/Wp, a performance ratio of 85 per cent and average sunshine for Frankfurt from 1981 to 2008. We calculate an annual cost degression of 20 per cent for 2012, falling to 10 per cent p.a. (from 2015) and amounting to 5 per cent from 2020.

The federal government's planned rise in regenerative energy's contribution to electricity generation requires adjustments to be made to the existing power station structure. Table 9 shows how wind energy and PV capacity could be expanded by 2025 and 2040. This scenario, which we are taking as our starting point, also illustrates the drop in conventional (including adjustable) potential if, apart from the power stations currently under construction, there are no further new builds and old power stations are decommissioned in accordance with their assumed service life.[6]

The risk of supply bottlenecks in 2025

In line with the reduction targeted by the federal government, we calculate that net electricity consumption will fall from 538 TWh in 2010 to 484 TWh in 2025 (reduction of 12.5 per cent) and to 430 TWh in 2040 (reduction of 20 per cent). The slowdown in consumption will certainly tend to diminish the risk of a temporary undersupply. Another buffer is the present surplus electricity which Germany has been exporting since 2003 (2010: 17.7 TWh). If the 2010 capacity utilisation rates are to continue to apply in future, the reduction in conventional capacity will produce a 10 TWh demand for electricity in 2025 which cannot be met, whereas an overproduction of 16 TWh can be expected in 2040. The supply bottleneck in 2025 could be relieved by importing electricity, by a temporary (moderate) increase in the capacity utilisation of conventional power stations or by new builds of gas, coal or biomass power stations.[7]

Flexible power stations as an option

When using flexible conventional power stations to balance power demand and supply, a minimum capacity utilisation is essential. Frequent downtimes and running at low utilisation rates mean less profit while still incurring fixed costs. Operating in load following mode also leads to additional wear, less efficient use of fuel and higher costs. Despite this, even if there were to be noticeably lower capacity utilisation in 2025 (a reduction from 37 per cent to 25 per cent for gas and steam power stations), the rise of 1.5 cents/kWh in the production costs of gas-fired power stations would still be moderate. This implies that the capacity utilisation problem can be kept within bounds and that building additional flexible gas-fired power stations could be thoroughly worthwhile. The option of relieving bottlenecks by using flexible power stations is one conceivable (partial) solution to the renewables problem for the transitional period.

achieved. On average, the degree to which wind and PV capacities are utilised is well below that of conventional power stations. This is due to a far more dramatic increase in capacity than in annual power generation.

[6] If no new power stations are built, the assumption on which this scenario is based will lead to an even greater rise in the proportion of annual production accounted for by renewables. The wind energy proportion rises from 15 per cent to 26 per cent (2025) and 35 per cent (2040), mainly due to the increase produced by offshore systems and to much bigger, more sophisticated new build and repowered systems. The PV contribution would grow from today's 1.9 per cent to 9 per cent (2025) and 19 per cent (2040). Both PV modules and system components such as inverters are becoming significantly more efficient and are already achieving efficiency levels of 16-18 per cent (inverters: 98-99 per cent).

[7] An increase from gas, biomass, coal and lignite-fired power stations by ten percentage points (lignite: increase of 5 per cent) to 47 per cent, 58 per cent, 56 per cent and 87 per cent respectively would be sufficient.

Power plant flexibility 12

Average Germany, 2011

Load following capability

Minimum capacity utilisation (%)

	New plants	Old plants
Gas and steam	25-30	40
Gas turbine	0-20	
Coal	35-40	55
Lignite	50	60-70
Nuclear power		70 (90**)
Storage plant	0	0

Partial load behaviour

	Efficiency loss (%-age points)	Output change (% / minute)
Gas and steam	11****	8-10
Gas turbine	22	15-20
Coal	6	4-6 (2*)
Lignite	5	2-3 (1*)
Nuclear power	5	4-5**
Storage plant	0***	up to 100

Reserve suitability*****

Time to run up to full capacity (minutes.)

	Cold start	Warm start
Gas and steam	120	30
Gas turbine	25	< 10
Coal	300	120
Storage plant	< 2	

* Old plants, ** Lower (upper) output range,
*** Power plant often with several turbines, capable of being individually shut down or adjusted. Depending on how adjusted, losses of up to 10 percentage points at 40% capacity utilisation,
**** 0% at 87-100% capacity utilisation,
***** Lignite and coal-fired power plants unsuitable.

Sources: DB Research, RWE, Areva, Federal Environment Agency

Electricity storage has many applications

The challenges posed by conventional power stations, that of producing CO_2 and (e.g. at times of strong winds) of leaving part of the green electricity unused, do not arise with electricity storage, the second tool used in the past. It has so far been used to store base load power inexpensively at low load times (often at night) and to deliver it subsequently at high prices at peak load times (‘electricity price enhancement’). Storing electricity gave power station operators several simultaneous advantages, namely the ability to exploit price differentials, optimum capacity utilisation and generation at minimum cost. Furthermore, by using positive and negative capacities, they were able to provide system services. Already today, the service element can represent between a third and a half (sometimes even as much as two thirds) of storage system operators’ business volume.

Is grid relief a new application area?

Storage systems could help to provide grid relief whenever overload occurs at nodal points or in sub-sections, i.e. when grids are not able to accept power feeds from wind and solar power systems (often from separate lower voltage level systems) or supply consumption centres in distant regions. In 2009, 127 GWh (98.7 per cent of which was generated from wind power) was lost because grid operators had to shut their systems down. Although these losses represented a 70 per cent increase over the previous year, this only equates to 0.34 per cent of the wind energy fed in.[8] In our estimation, this is mainly a wind power problem that will continue in the medium term (up to 2025), firstly because power generation is centred in northern Germany far away from the main centres of consumption in the south. Secondly, because the generation pattern is essentially different, it is not possible – as it is with PV – to increase consumption by incentivising individuals to consume their own wind-generated energy. During normal operation, storage systems have only a limited potential for preventing this problem. According to the Dena Grid Study II, building more storage systems would, at best, lead to a slight reduction in the requirement to extend and upgrade the grid.[9] In any event, extending the grid is a vital precondition for a successful energy revolution.[10]

Renewables need more adjustable output capacity

Forecasting electricity generation from wind power and PV is far more challenging than forecasting consumption. Whereas the forecasting error for PV in Germany has a standard deviation of 2.5 per cent, it is 12-14 per cent for wind power (for 2007 and over a timeframe of two hours) depending on the region concerned; in extreme cases it even represents 21 per cent of the wind turbine fleet output.[11] Accordingly, both positive (and negative) adjustable output needs to be kept in readiness, currently amounting to less than 20 per cent (10 per cent) of the wind energy generated. Already, using storage systems in this way can in many cases make up the majority of an operator’s profits. However,

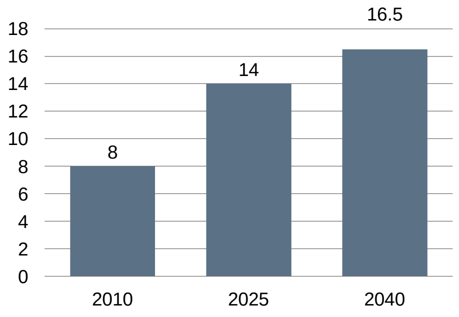
[8] Federal Network Agency (2011). Monitoring Report 2011. Bonn.
[9] The reason is that storage system operators negotiate system services in the market or exploit electricity price spreads, but operators do not build up storage capacity to cushion grid bottlenecks. However, it is conceivable in future that political incentives could allow storage systems specifically designed for grid relief to be built and thus reduce the need to expand the grid (hybrid power stations). However, wind energy would still have to be moved from the north to the south.
[10] Depending on the solution adopted, the expansion of the transmission grid will involve between 1,700 and 3,600km of new power lines and the modification of between 0 and 5,700km of existing routes. This will cost between €0.9 and €1.6 billion each year and will result in grid usage charges rising by between 0.2 and 0.5 cents/kWh to between 6.0 and 6.3 cents/kWh for domestic users (Dena Grid Study II).
[11] Deutsche Energie-Agentur GmbH Dena (2010). Dena Grid Study II. Berlin.

according to Dena (Grid Study II), the forecasting error will reduce by 40-50 per cent by 2020, thanks to better forecasting methods. Nonetheless, doubling the volume of wind energy fed in to the grid will require the error to be reduced by more than 50 per cent, if additional adjustable output is not to be kept in readiness.[12] We expect that the forecasts will show a 65 per cent improvement by 2025 and be 85 per cent better by 2040. As a result of the growth in wind-generated electricity and also taking the (more accurately forecastable) PV into account, the adjustable output requirement compared with 2010 will rise by 50 per cent by 2025 and by 70 per cent by 2040. Greater decentralised generation and the major feed-in volatility of the renewables will also increase the requirement for additional system services. Considerably more adjustable output will be needed in future overall.[13]

Preventing surpluses and undersupply

Adjustable output required* 13

Germany (TWh)



* Positive adjustable output to compensate for forecasting errors

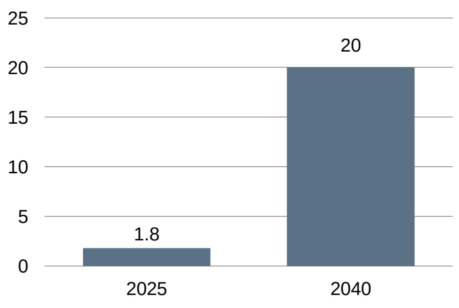
Source: DB Research

Storage systems can be used if the volume of non-adjustable electricity generation temporarily exceeds consumption (either within a grid or within a geographically defined area), or if consumption cannot be satisfied by the generation capacity which can be called upon. Even the operators themselves often have difficulty in estimating the extent to which storage capacity is currently used for balancing renewables (smoothing and system services) on the one hand and classical operation on the other.[14] The proportion used for balancing renewables has recently seen strong growth and, with some storage systems, can account for most of the profit.

From a simulation study, based on hourly consumption, wind and PV feed-in data for 2010 and 2011 and on the basic scenario described above, we estimate that surpluses would only accrue at federal level today in the order of magnitude of 15 GWh (0.1 per cent of the annual production of wind and PV generated electricity), assuming the grid had been expanded so that it could in theory transmit 100 per cent of the energy produced by renewables within Germany. Positive (not reducible at national level by expanding the grid) surpluses will rise to 3.5 TWh, or 2 per cent of annual production, by 2025. This still rather moderate volume, a result of declining ‘must run’ output, will amount to almost 40 TWh (or 14 per cent of PV and wind-generated electricity) by 2040.

Electricity surpluses to be stored* 14

Germany (TWh)



* Assumption: 50% of all electricity surpluses will be stored

Source: DB Research

The volume which cannot be directly covered by wind and sun amounts today to 260 TWh and will, in our scenario, be 220 TWh in 2025 and 115 TWh in 2040. Those residual load power stations, which are currently either operational or under construction, will not be sufficient to cover this supply gap in future. In 2025 and 2040, a shortfall of at least 4.5 and 12.5 GW respectively will remain, which will need to be covered by new power stations, more closely integrated European grids or positive storage capacity.

Storage over different timeframes is essential

Because fluctuation patterns for PV, wind and power consumption vary, it may also be necessary to provide storage capacity for timeframes of differing lengths: 1. for a few minutes (feed-in fluctuations); 2. up to one day (daily PV pattern); 3. up to three days (random PV fluctuations); 4. for one to two weeks (periods of sustained strong or light winds); 5. seasonal timeframes. Our

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12 Klobasa, Marian (2007). Dynamic simulation of a load management system and the integration of wind energy into an electricity grid at national level from control engineering and cost aspects. ETH Zurich.

13 Estimating the order of magnitude of these system services is not easy, making it impossible to quantify them precisely here.

14 The rate at which electricity is drawn off from and fed into the grid is determined by market prices, which themselves follow from the relationship between overall electricity production and consumption.

analysis shows that, to cover all these circumstances, there will still only be a requirement for storage for periods of minutes or hours in 2025. In contrast, by 2040, storage capacity for weeks and, although to a relatively small extent,[15] for entire seasons will be necessary in order to use electricity from renewables and to safeguard power supplies in winter.

2. No obstacle is insurmountable

Various static, centralised and grid-connected solutions are available to satisfy the significant requirement for electricity storage systems with different capabilities which will arise both in the medium (by 2025) and the long term (by 2040).

2.1 Pumped storage power plants and storage power plants

Pumped storage power plants (PSPs) use electrical energy to pump water from a lower reservoir up to a higher reservoir, into which either no other or only small additional streams feed, and where the converted electrical energy is stored in the form of the water's potential energy. When required, the water flows under pressure through a pipe to turbines whose generators produce electricity. When the water is pumped up, the generators act as motors for the pumps which, in newer plants, can themselves be the turbines. The volume which can be stored depends on the size of the storage reservoir and also, like the output from the turbines, on the difference in height (up to 600 m in Germany).

Great flexibility is a decisive advantage

Black start capability is fashionable 15

Power stations and storage systems (such as PSPs, gas-fired stations and compressed air storage systems), are black start capable if they do not need any electricity for them to generate electrical energy themselves or for starting-up (e.g. nuclear power). By being able to start themselves and other power stations in the event of power outages, they ensure security of supply.

One major advantage of PSPs is their outstanding flexibility. For example, the average plant is capable of being run up to maximum performance within 75-110 seconds, of being shut down again if the load suddenly drops and converted to full pump operation within approximately three minutes. Particularly flexible plants can even run the pumps and the turbines up from stationary to maximum load within 30 seconds. If several pipes are installed, pumping and turbining in parallel can simultaneously provide negative and positive adjustable output. In Germany, the negative output, i.e. absorbing the electrical power by using it for pumping, represents on average 94 per cent of the turbine power. This ratio is not fixed and can be varied. Because of these negligible losses, the storage period is theoretically unlimited.

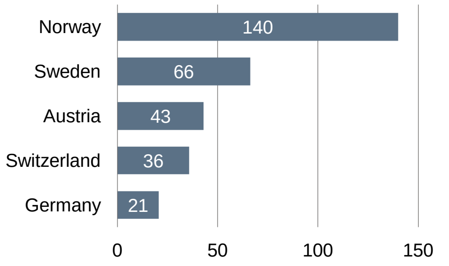
PSPs predominate within Germany

In Germany, PSPs account for 95 per cent of the available output from grid-connected storage systems. They are important from both a technical and an economic aspect in that they carry out all the 'classic' functions of storage systems. The turbine power of the more than 30 German plants represents 6.3 GW of pumped storage output and 40 GWh of storage capacity. As a consequence of the federal government's decision to incentivise those PSPs which start operating before 2019 by exempting them from the grid usage charge for ten years, we calculate that, by 2025, at least 4 GW of the projects currently being considered will have been realised. By 2025, this will raise the turbine output from all the PSPs in Germany to 10.6 GW and increase storage capacity to 64 GWh. Despite frequent public opposition, we expect in the long term that, of the total but as yet unexploited installable potential (approximately

[15] Taking the year as a whole, electricity generation from wind and PV evens out. In Germany, assuming a ratio of 4:1 between wind power and PV and even assuming 100 per cent reliance on renewable energy, seasonal energy storage would only be necessary to a small extent. However, by 2040, the ratio will be in the 2:1 range.

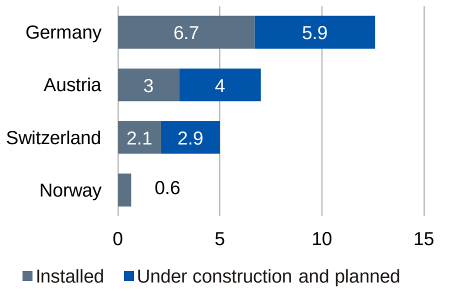
Hydroelectric power 16

Annual production (TWh)



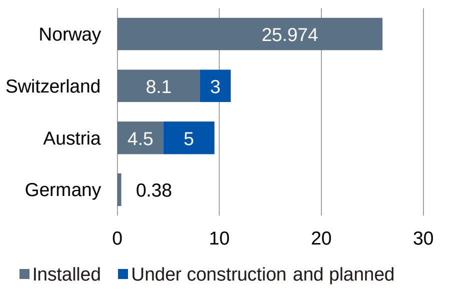
Turbine output, PSPs

(GW)



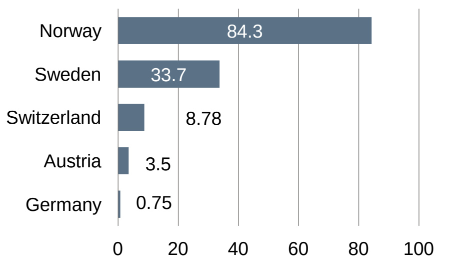
Turbine output, storage power plants

(GW)



Water storage capacity

Completely full (installed TWh)



Sources: BDEW, Energy in Norway, Österreichs Energie, BFE, Svenski Energi

10 GW), 8 GW could be realised. Consequently, turbine output of 14.6 GW and 87 GWh of storage capacity would be possible by 2040.

In addition to new builds and expansion of existing PSPs, storage power plants could also be modified to include a pumping function.[16] However, configuring the pumping function in this latter option is subject to restrictions because most storage power plant upper reservoirs (unlike those of the PSPs) are natural and designed so that the water level must neither exceed nor fall below certain limits. Also, if fed by minor streams with no means (e.g. an equalising reservoir) of absorbing major fluctuations in water level, the lower reservoir is a further limiting factor. Despite this, such functional enhancement is both technically possible and ecologically practicable in many cases. However, any increase in the number of storage power plants in Germany is unlikely, since their output is still less than that of the adjustable run-of-river power stations (516 MW).[17]

Major potential in the Alpine countries

PSPs with a pumped storage output of 3 GW have been installed in Austria. The annual production from storage power plants is 13 TWh (19 per cent of total power production). There is an unexploited technical and commercial opportunity for increasing the total annual generation of hydroelectric power by 13-18 TWh (30-40 per cent); (the target for 2020 is an increase of 7 TWh). Of this, 2.1 GW will come from PSPs and storage power plants under construction and 1.6 GW from those awaiting a licence.[18] A large proportion of the Austrian storage power plants are already equipped with a pumping function – as PSPs which rely largely on a natural water feed. Other conversion plans exist. Construction work (storage power plant conversions) has already begun to enable Switzerland to achieve its expected 2.9 GW growth in PSPs. The annual production from existing storage power plants is 17.4 TWh or 49 per cent of all hydroelectric power. Of the maximum 8 TWh potential for expanding hydroelectric power, a net addition of 4 TWh is currently being targeted.[19]

Scandinavian water storage of massive proportions

Norway[20] has plans to increase its annual production of 122.7 TWh by 9.2 TWh, which will reduce the unexploited potential realisable under nature conservation legislation to ‘just’ 28.1 TWh. However, only 640 MW of PSP turbine output is installed. Since approximately 90 per cent of all hydroelectric power is generated by storage power plants, these could be equipped with PSP functions. Sweden, too, has very large water storage systems, but only has one PSP installed. Building power line links to Norway will allow price differentials to be exploited and wind-generated energy transmitted to Norway whenever Germany produces more than it consumes. In turn, inexpensive Norwegian electricity from storage power plants is to be transmitted to Germany, where

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[16] In some cases, this is already a reality, often making it difficult to distinguish clearly between PSPs and storage power plants.

[17] This represents 17.6 per cent of all run-of-river power stations. Adjusting output is made easier if several run-of-river power stations are installed one after the other or if storage power plants are installed upstream – particularly if (as is partly the case in Austria) a level fluctuation of up to 15 centimetres caused by turbining does not interfere with operations. Cf. Müller, Hildegard (2011). Hydroelectric power is the ideal energy revolution partner. Hydroelectric power – in Germany. German Association of Energy and Water Industries (BDEW). Berlin.

[18] Österreichs Energie (2011). Electricity in Austria 2011. Vienna; Österreichs Energie (2011). http://oesterreichsenergie.at/

[19] Swiss Federal Office for Energy (2011), http://www.bfe.admin.ch/themen/00490/00491/; Swiss Water Industry Association (2011). Potential for expanding hydroelectric power in Switzerland. Baden. It should be noted that achieving this target under present conditions is disputed and assumes a partial drop in production.

[20] Energy in Norway 2008 (2009). Norwegian Water Resources and Energy Directorate.

Electricity exchange 17

In 2010, Germany exchanged 17.1 TWh of electricity with Austria, 7.7 TWh with Switzerland and 3.4 TWh with Sweden.

See RWE Facts & Figures 2011

Links to Norway's storage systems 18

NorGer is a 600km-long high-voltage power cable, linking Germany and Norway. Initial start-up is planned for 2015 with a capacity of 1.4GW. Cost: €1.4 billion.

Nord.Link is another 580km-long cable which will link both countries. Initial start-up is envisaged for 2018-2021 with an output of 1GW.

NorNed is a 580km-long high-voltage cable between Norway and the Netherlands which has been in operation since 2008; its transmission capacity is 700 MW.

Connections for Denmark and the United Kingdom are also planned.

See http://www.statnett.no/en/Projects/

Important terminology 19

Diabatic or D-CAES employ a gas or oil-fired system to heat the air during the expansion process. The relatively proven technology is already in operation in the Huntorf power plant. In 2006, the plant was upgraded by 31 MW from its initial 290 MW.

Recuperator describes a device, which recovers the exhaust heat produced at the turbine by the gas-fired process in order to re-use it to pre-heat the air. Its installation in the D-CAES in McIntosh, Alabama represents an improvement, increasing the plant's efficiency by 12 per cent.

Advanced Adiabatic or AA-CAES is a further development of the CAES which aims to recover and store the heat generated by the compressor during the compression process. Using it to heat the air during the discharging process is intended to replace the additional gas-fired procedure.

generation costs are higher. The battery effect comes from exchanging wind-generated energy for storable, potential electricity from storage hydropower plants, without first having to incur losses by converting the wind-generated energy into potential hydroenergy or having to use renewable electricity to refill the storage reservoirs. This indirect method of storing electricity produces the same result as direct storage, but with fewer losses (5 per cent).

In addition, the grid will need to be expanded if it is to link up with the Alpine countries; this is, however, less complex to achieve and, particularly in the case of Austria, already well-established. One problem is that plans exist in both Scandinavia and Switzerland for an expansion of PV and wind energy. These countries will then, themselves, have a growing requirement for storage capacity, meaning that a degree of uncertainty will attach to access to such capacity and it may only be possible to a limited extent.

New energy from the pits?

Another idea, already discussed earlier in Germany and the Netherlands, is to construct PSPs underground – in decommissioned mines or purpose-designed excavations. These would contain one or both reservoirs on two or more levels, with shafts linking and connecting the cavities to each other.[21] Useable height differences of between 400 and 800 m and up to a maximum of 1,750 m have been mentioned. Clausthal University of Technology estimates the potential at some 20 GWh and talks of approximately 100 suitable mines. In addition to great differences in height, one major advantage is that no land is taken up on the surface. Nonetheless, existing mine galleries need to be reinforced to prevent them collapsing. The mining and conventional PSP construction sectors already possess the essential engineering techniques. Although the latest PSPs are mostly installed in underground chambers (the machinery hall and the pipes are all below ground), these projects are demanding because the cavities need to be sufficiently large if they are to be used as storage reservoirs. Rock formations similar to coal seams are necessary to ensure the water is of adequate purity and to prevent it leaching away.[22]

2.2 Compressed air energy storage

Compressed air energy storage (CAES) uses electricity to compress air to between 40 and 120 bar and then to cool it using cooling elements. The converted electrical energy is stored in cavities 700-900m below ground in the form of pressurised gas. Decompression reconverts the gas, during which process the air has to be heated before flowing through modified gas turbines. Those system variants, which are either operational or at the planning stage, differ as regards the heating method employed or how the heat losses at the compressor and turbine are managed. The recuperator function (see box opposite) in McIntosh, Alabama, represents a moderate improvement which may be expected from new D-CAES systems. The adiabatic function implies a technological leap to a practically new type of storage system.

Both the existing D-CAES plants are used commercially for electricity price enhancement; they provide system services and offer a black start capability. However, none of the various projects in the USA has been built because of the

[21] Depending on the circumstances, a variety of designs should be possible in which natural basins or the topmost level of a mine could be used as the upper reservoir. The lower reservoir can be an impermeable level, either as it was left when abandoned or after some additional preparation.

[22] Although technically possible, this could be too expensive. Since no such projects have been completed, there is relatively great uncertainty about the cost and the technical problems which might arise. However, in certain circumstances, a project like this might be a thoroughly realistic prospect.

Compressed air energy storage 20

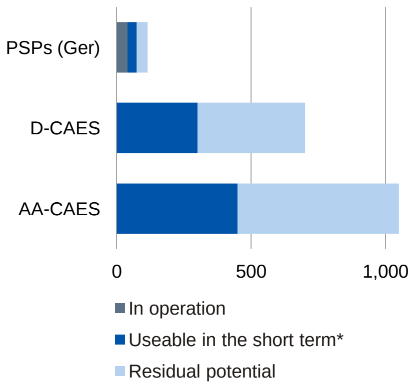
Existing plants and planned projects

	Huntorf	McIntosh
Turbine (MW)	321	110
Compressor (MW)	60	60
Volume (1,000 m^3)	300	538
Storage cap. (MWh)	580	2860
Max. full load hours	2	26
Commissioned in	1978	1991
Efficiency (%)	42	54
	Norton	ADELE
Turbine (MW)	2700	90
Compressor (MW)	–	60
Volume (1,000 m^3)	10000	120
Storage cap. (MWh)	518000	360
Max. full load hours	190	4
Commissioned in	–	2016
Efficiency (%)	60	70

Sources: DENA, RWE, DB Research

Short-term storage volume 21

(GWh)



* PSPs: under construction and planned; CAES: volumes, if all natural gas storage system (in operation, under construction and planned) could be used

Source: DB Research

economic crisis. AA-CAES systems are intended to carry out the same functions as D-CAES systems but have so far only reached the development stage and only exist as plans. Although research into the engineering principles is largely complete, they have not been developed for this specific application and remain untested. In Germany, a consortium made up of manufacturers and energy companies is working on a project in Strassfurt.

Not fully proven until fired up

It is mainly the heat storage system and the compressor which require further development and testing. The turbines also need to be optimised for purely compressed air operation. In the absence of any practical experience, there is a degree of uncertainty about how they will actual behave. It may, however, be assumed that AA-CAES will be available in a few years (before 2020).[23] In contrast, the D-CAES does not need a heat accumulator. Also, being closely related to a gas-fired power station,[24] traditional turbines can be used after only relatively moderate modification.

CAES can be employed extremely flexibly

CAES systems allow very flexible operation and, because their technology is closely related, their start-up behaviour is similar to that of gas turbines. They are more versatile than gas and steam power stations, particularly if simpler, smaller and thus more flexible turbines (in the mean pressure steam turbine range) are used. With new AA-CAES systems, it should be possible to run up the turbines and compressors from 0 to 100 in 10-15 minutes. Although they do not achieve the same operational dynamic as PSPs, having two cavern access shafts makes it possible to provide positive and negative adjustable output simultaneously. Although the AA-CAES heat accumulators do not permit unlimited storage periods, this does not present a problem for the way existing D-CAES systems work nor for how future AA-CAES systems are forecast to work.[25] Compressed air energy storage systems can be flexibly configured as regards the relationship between turbine output, compressor power and storage capacity – the same applies to the size of the plant: the D-CAES project in Norton, Ohio, which was not implemented, was supposed to deliver 2.7 GW of turbine output from eight days of full-load operation with nine 300 MW units.

There is still major potential for expansion

So far, salt caverns have been scoured out to create storage reservoirs. Using caves, aquifers, pore storage and mines is also under discussion. There are numerous suitable locations: salt domes in Lower Saxony, Schleswig-Holstein, Mecklenburg-Western Pomerania and other European countries (e.g. Poland and Spain) have been tested and found to have great potential. Germany has caverns, in operation, under construction and planned, with a geometric volume of approximately 150 million m^3 for storing natural gas. Taking technical and ecological restrictions into account, it is estimated that there is an additional potential of approximately 200 million m^3 in Germany.[26]

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23 RWE Power (2010). ADELE – the adiabatic compressed air energy storage system for supplying electricity. January 2010. Essen/Cologne; Calaminus, Bernd (2009). Adiabatic compressed air energy storage systems as an option for bulk electricity storage. EnBW.

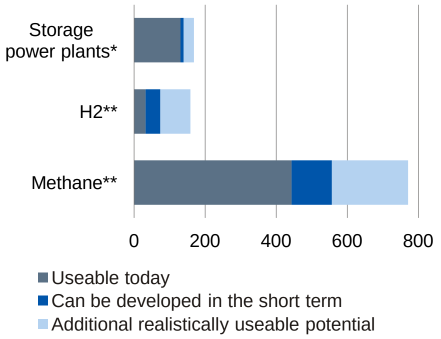
24 Strictly speaking, the D-CAES is a mixture of a gas-fired power station and an electricity storage system because delivering 1 kWh of electricity requires the input of approximately 0.8 kWh of stored electricity and 1.3 kWh of gas. The function performed by the gas turbine's compressor is replaced by the compressed air.

25 The stored heat is still enough to drive the turbines two to three days after it was stored.

26 Fraunhofer (2010). Energy target 2050. July 2010. Sedlacek, R. (2009). Underground gas storage in Germany. Oil, natural gas, coal. 125th annual edition. Booklet 1; Natural gas storage

Long-term storage volumes 22

(TWh)



* Germany, Austria, Switzerland, Sweden, Norway*
** Underground natural gas storage and natural gas pipeline grid

Sources: Oil, natural gas, coal 2011, Fraunhofer 2010, DENA 2011, DB Research

2.3 Hydrogen and methane storage

The disadvantage of the mechanical storage systems discussed so far is their lack of, or only limited, long-term storage capacity. Apart from large storage power plants, they are only designed to operate for storage cycles of hours or a few days and, as such, they carry out all those functions which are needed up until 2025. However, they are not capable of compensating for regular week-long periods of strong or light winds or seasonal fluctuations. However, this is precisely what will be needed by 2040. Power-to-gas storage could solve this problem.

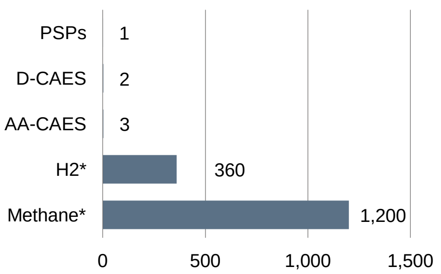
Hydrogen (H2) can be produced from water and electricity by means of electrolysis. It has a very high energy density and can be stored in caverns practically without loss in virtually unlimited quantities for unlimited periods.[27] This makes it ideally suited for storing energy for periods of weeks or whole seasons. H2 can be converted back into electricity using fuel cells, gas turbines or gas-powered engines.

Hydrogen production still in its infancy

A variety of electrochemical production technologies are available. The least expensive and most frequently used is alkaline electrolysis. It is currently used for industrial applications and has a power output range of a few megawatts. It has some optimisation potential for commercial energy use.[28] Hopes are based on its low power consumption, even with high-temperature electrolysis, although the prototypes only have a short service life.[29] In (negative) load compensation mode, electrolyser efficiency can deviate from optimum performance and drop by up to 8.5 per cent; however, this represents only a slight problem for seasonal compensation, for example, when temporary fluctuations can be compensated for by other types of storage. In addition, efficiency levels under partial load are greater than under rated load. Reaction to load alternation and load step changes occur almost instantaneously over the entire partial load range, and start-up from 0 to 100 and shutdown from 100 to 0 are both achievable in less than 15 minutes (more quickly than with gas turbines).[30]

Energy density of storage media 23

(kWh/m3)



* Underground storage at 200 bar

Source: DB Research

Highly-promising storage and transportation conditions

H2 can be stored in various ways. In addition to the aforementioned storage in caverns (inexpensive, a favourable technical option and already tested by the chemical industry[31]), adding H2 to natural gas and transporting it in pipelines could now be of interest to the energy industry. No significant volatility or performance degradation problems are expected if H2 represents up to 5 per cent of the volume (or 1.5 per cent of the energy). In the medium term, this proportion could rise to between 10 and 20 per cent. Since the 500,000 km-long grid has a storage capacity of over 200 TWh of natural gas and is able to transport 1,000 TWh of energy per year, 3 TWh of H2 could be stored at any time and 15 TWh over the course of the year (9 and 45 TWh in future). [32]The

reservoirs are of far greater volume and on average somewhat deeper than CAES caverns. Partly because salt domes are at greater depth and very sizeable, we do not envisage any problems caused by competition for their use.

27 Hanning, Florian and others (2009). The status and potential for development of electroenergy storage techniques. Fraunhofer ISE, Fraunhofer AST and VKPartner.

28 Hanning and others (2009).

29 Dena (2010).

30 Fraunhofer (2010).

31 Dena (2010 b). Analysis of the need to increase the capacity of pumped storage power plants and other electricity storage systems so as to integrate renewable energies. Berlin.

32 Dena (2011), Engineering and technology development thesis, http://www.powertogas.info/thesen/thesenpapier-technik.html; Albrecht (2010). Other storage options exist but they are of less interest here. For example, with compressed gas storage, 15 per cent of the energy is lost during the compression process. Liquid gas can be stored at great

grid has a relatively high transport capacity; a 1m-diameter gas pipe can carry approximately 18 GW (compared with the 3.6 GW for a maximum voltage line). At approximately 1 per cent, gas pipeline transmission losses are considerably less than those of power lines (approximately 4 per cent).

Several options for reconversion into electric energy

It is possible to convert the mixture of H2 and methane, mentioned above, back into electricity in gas and steam power stations; this has the advantage of using a mature technology without the need for additional development or to build any new infrastructure. Alternatively, it is also possible to include H2 combustion in biomass and coal-fired power stations. Since it can make good energy policy sense to encourage the construction of new gas and steam plants in addition to the existing ones (see above) and thus to have a relatively large gas and steam capacity installed, it would then be possible to convert larger quantities of H2 back into electricity. Consequently, this suggests itself as a sensible bridging technology until more efficient, less expensive processes have been developed for converting H2 in its pure form back into electricity.

H2 turbines should be capable of achieving the same level of efficiency as today's gas and steam plants.[33] Electricity can also be generated in fuel cells in which H2 reacts with oxygen and recombines by means of H2 oxidation and oxygen reduction to form water. The drawbacks at present are the costly and complex systems engineering and the fact that plant size is still restricted to below the megawatt range. On the other hand, their flexibility and excellent partial load behaviour are ideal for smoothing daily operations.[34]

Methane synthesis as an interesting option

Mature technologies for storing, transporting and converting natural gas into electricity exist and are fully operational. Natural gas consists almost entirely of methane which, by taking the electrochemical process one stage further, can be produced from H2. The product of the reaction, which uses CO_2 from the air or from waste gases (e.g. biomass), has even greater energy density and lower volatility. Like H2, methane can be used as an industrial raw material, as a heating fuel or as a fuel for vehicles or other means of transport; the technology for using methane for these applications, too, is more advanced. The major disadvantage is that the most problematic stage in the storage cycle, electrolysis, cannot be circumvented and an additional transformation has to be undertaken. Of necessity, this reduces yet again its poor efficiency level and makes an already unfavourable cost situation even worse.

Nevertheless, several companies are working on a variety of projects and commercialisation strategies for the practical application of both electrochemical storage media. Current examples are work on methane production plants with a 20 MW output, the development of electrolysers with outputs as high as the hundred MW range and the commissioning in October 2011 of a hybrid power station for producing H2 (with a 500kW electrolyser output, H2 storage system and H2 biogas combined heat and power plant).[35]

Efficiency levels of storage systems 24

(%)

	Charging	Discharging	Overall
PSPs	88	92	81
AA-CAES	80	87	70
D-CAES	73	82	60
H2*	82	60	49
Methane*	67	60	40

* Gas turbine, cavern storage

Source: DB Research

density but is extremely expensive as a temperature of -253° is required. Although chemical storage in metal hybrid storage systems increases density still further, it is very expensive and involves particularly heavy storage and transport containers. Cf. Mahnke, Eva and Jörg Mühlendorf (2010). Storing electricity. 'Renews Spezial'. Renewable Energies Agency. Edition 29 / April 2010.

33 Gas turbines are more flexible and can, to an extent, burn oil and other fuels or, as described, be converted for use in CAES power plants.

34 Hanning and others (2009).

35 Rieke, Stephan (2011). The methanisation of eco-electricity. SolarFuel GmbH; Albrecht (2010).

3. Efficiency and cost analysis

The above description of the technologies shows that there are storage systems whose technical operating characteristics and potential for expansion make it possible to satisfy the needs of renewables. What remains unanswered, however, is the burden which these developments will force society to shoulder and the cost of the proposals.

Pumped storage systems are the most efficient at present

The most technically mature PSPs achieve by far the greatest overall efficiency and thus the least loss of electricity during its storage and discharge. Depending on age and configuration (e.g. height differential, size), average efficiency levels in Germany are 70-80 per cent (60 per cent and 83 per cent in extreme cases). Depending on the design, efficient plants lose approximately 12 per cent of the energy during pumping operations and 8 per cent when turbining.[36] D-CAES have a considerably lower cyclical efficiency level. However, the recuperator in McIntosh, for example, made it possible to increase this considerably, by twelve percentage points, to 54 per cent. For new plants, it was estimated to be even higher at up to 60 per cent.[37] But it is only AA-CAES, with their 70 per cent efficiency level, which are able to move up into the efficiency category of the weaker PSPs. Since the technology is still being developed, this figure could rise to 80 per cent. The losses amount to approximately 20 per cent when charging and 13 per cent when discharging. Still relatively inefficient are the electrochemical processes. An efficiency level of 70-82 per cent is achievable with alkaline electrolysis. The past trend towards improvements will continue in future.[38] Although virtually nothing is lost during cavern storage, gas turbines and fuel cells incur losses of 60 per cent and 45-55 per cent respectively[39], implying an overall efficiency level of 39-49 per cent. Energy losses of 18-25 per cent[40] reduce the efficiency of storage based on methanisation to 33-40 per cent with the technology available today.[41]

Electrochemical processes inefficient

Compressed air energy storage with the lowest capital investment costs

Technical progress foreseeable

The capital investment costs for PSPs vary widely and are currently estimated at EUR 800 to 1,300 per kW of installed power. There are many reasons for the significant differences in cost: caverns and galleries may need to be excavated to take the pipes, the geographic circumstances may vary and PSPs may have to be constructed from scratch or storage power plants upgraded.[42] This expenditure may be seen in perspective if a service life, generally set at 50 years but more likely of 80 years, is taken into account. Depending on the size of the storage system, the cost of D-CAES is comparatively low at EUR 500 to 800 per kW (at the bottom end of this range for 1 GWh and at the higher end for 5 GWh). As for AA-CAES, the cost will be 30-40 per cent higher, at between EUR 700 and 1,000 per kW, due to the extra expenditure needed for heat

[36] Gloor, Rolf (2010). Pumped storage power plant. Viewable at http://www.energie.ch/pumpspeicherkraftwerk/print. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, BMU. (2010). Calculation of the potential for expanding the use of hydropower in Germany. Aachen.
[37] Rieke (2011).
[38] Fraunhofer (2010). Energy target 2050. July 2010. Dena: 443.
[39] http://www.iwr.de/re/iwr/09/09/2402.html
[40] Fraunhofer July 2010, Energy target 2050, Pages 36-37, 44, Dena (2010).
[41] If synthetic methane is used as the fuel, an efficiency level of 48-65 per cent can be expected, whereas that of H2 rises to 64-78 per cent.
[42] The cost of expanding or extending a plant often works out as the same as that for a new build. The sites are more important. Estimates for underground PSP plants amount to EUR 1,300 per kW but they can only be built on appropriate sites.

accumulators and heat exchangers.[43] Of course, development costs will make the first plants more expensive (between EUR 1,000 and 1,400 per kW). Despite being frequently run up and shut down, CAES systems have a relatively long service life. Regular maintenance should increase their service life from the 30 years originally set by their operators to at least the same as that of gas-fired power stations, i.e. 40-50 years.[44] At present, H2 and methane storage is the most costly. The cost of electrolysers and methanisation plants can be estimated at approximately EUR 1,000 each per kW. The expensive components, the electrolyser and the fuel cells, are still only being produced in small numbers and on a small scale. The service life of the electrolyte system is currently approximately 20 years. With an estimated service life of up to 40-45 years for gas turbines and the almost unlimited life of cavern storage, reconversion and storage components are far more robust.

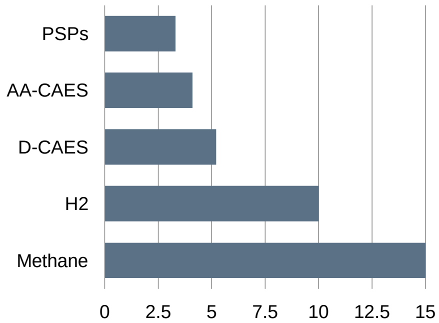
Still no genuine grid parity at present

Cost varies with technology

Compared with other power stations, the operating, servicing and maintenance costs for PSPs and storage power plants are very low. The costs for AA-CAES systems will also work out very favourably. If electricity and gas can be bought in very cheaply, D-CAES systems can be competitive, but they are subject to uncertainties as regards the trend in gas prices. Estimating average turbine utilisation is problematic since not all the system services available will be called upon. At an average of 1,000 full load hours per year (2.7 per day)[45] for German PSPs and 1,800 full load hours per day (four hours/day) at the upper end, one can assume at least 2,000 to 3,000 hours of capacity placed on the market each year. Due to their design, the capacity utilisation of existing CAES systems is lower but, for new plants it is also set at 4h/day. This results in system operators incurring average storage costs of approximately 3.3 cents/kWh for PSPs, 4.1 cents/kWh for AA-CAES and 5.2 cents/kWh for D-CAES (see chart 25).[46] According to our model, the total production costs for 1 kWh of renewable electricity in short-term storage amounted to 10.9 cents for PSP storage (the most economical renewable plants and storage systems) and 12.3 cents/kWh for AA-CAES systems in 2011. At 7.8 cents/kWh, the residual output from coal costs considerably less today.

Storage operators' costs 25

For daily storage (in cents/kWh*)



* Assumptions: technology as at 2011 (for AA-CAES: as at 2020); 2 cts/kWh electricity storage costs; plant usage period as stated in the text; 8 full load hours/day turbine operation + available system performance (physical storage system) not called upon; gas turbine reconversion to electricity and cavern storage (chemical storage system)

Source: DB Research

Renewable electricity on call is becoming competitive

Taking our forecast of an increasingly slow decline in costs for renewables and excluding improvements to the technology and the cost of the most efficient storage systems described, by 2025 the price for stored wind-generated electricity, available on call, could drop to 8.6 (9.7) cents for PSPs (AA-CAES) by using the most economical plants. In our relatively conservative scenario (see above) as regards the change in price for CO_2 certificates, gas and coal, the price for renewable electricity would be exactly the same as the cheapest conventional adjustable electricity price (this will be gas power in 2025).

Gas-fired power stations are helpful

Gas-fired power stations would be helpful in the transitional phase

As regards costs, storing electricity from renewables will only be beneficial in the medium term. Before then, it may be sensible to use gas-fired power stations to

[43] Madlener / Latz (2010). 1, 17-18.
[44] Turbine wear is less in CAES systems than in gas-fired power stations. Although the plants need to withstand relatively large variations in volume flow and pressure, the extremely high temperatures to which gas turbines are exposed are not experienced by the air turbines in CAES systems.
[45] That equates to a cycle frequency (from 100 per cent full to completely empty and back again) of 0.5 per day.
[46] It is not unusual today to assume electricity storage prices of 2 cents/kWh.

ensure supplies, even if the power stations are underutilised and electricity from renewables suffers a partial collapse. Additionally, as a transitional technology, gas and steam plants are also very compatible with long-term storage solutions – H2 and synthetic methane. These will probably not be sufficiently mature technologies by 2025. Certainly, the concept of European grid integration and using non-German hydropower should also be pursued further since these are relatively inexpensive alternatives.[47]

More development should go into electrochemical storage systems

Any commercially successful implementation of solutions based on H2 and renewable energy methane will not be possible in the medium term without subsidies (mainly because they are not yet cost-effective, are too technically complex and their development is still at an early stage). However, the service provided by systems capable of month-long storage will also not be urgently required in the medium term. By the time large-scale long-term storage becomes necessary within a timeframe of almost 30 years, great progress should have been made with electrochemical storage systems. Of all the technologies presented here, these have the greatest potential, thanks to their high energy density and versatile employability. In the next two decades, the capital investment requirement for new energy storage systems in Germany alone will total around EUR 30 billion.

4. Conclusion

The energy revolution relies on increasing amounts of renewable energy and therefore requires bigger storage systems, capable of meeting the greater demands which will be placed on them. The present market volume for supplying adjustable output for periods of a few hours and days will more than double in the medium term (up to 2025). Flexible electricity storage systems widely available today, such as PSPs, storage power plants and compressed air energy storage, are able to satisfy future requirements for flexibility. By 2025, the on-call energy they supply will equal the amount supplied by the most inexpensive flexible conventional electricity supply systems, whereas, depending on CO_2 emission costs, the non-adjustable (non-stored) renewables will be almost as expensive as the non-adjustable conventional systems.

In the long term (by 2040), there will also be a need – in addition to a moderate growth in the short-term storage requirement – to balance fluctuations in the electrical energy supply for weeks at a time. Electricity will also need to be stored for entire seasons to ensure supplies during the winter months. Until then, further research and development must be invested in chemical storage technologies. Expanding the grid at both national and European level and using the latest gas-fired power stations could represent an affordable contribution to risk reduction in the electricity sector.

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Jan Keil

[47] Both electricity prices and generation costs (storage power plants: 1.5-3.5 cents/kWh) are in some instances much less expensive than in Germany. The electricity transmission costs from Norway to Germany would amount to less than 1 cent/kWh.

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