Electricity Storage Technologies for Short Term Power System Services at Transmission Level

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Content

1. Introduction

Electricity is volatile commodity and has to be consumed at the same pace it is produced. In other words: production of electricity must be adapted to consumption at a very short notice if grid stability shall be maintained. Disturbances in production and changes in demand imply frequency deviations in the grid and to prevent such deviations the Transmission Service Operator (TSO – in Denmark Energinet.dk), who is the overall responsible entity for grid stability in the Danish power system, buys services (ancillary services) that can maintain the balance, when changes in demand or supply occur. Energinet.dk buys ancillary services from producers and consumers of electricity. Currently, Energinet.dk regularly buys the services described in Section 2.1 and a substantial part of the services are provided by owners of existing fossil power plants, e.g. conventional central power plants or de-central gas engines, who are active on the market for ancillary services.

The electricity supply system in Denmark has changed dramatically over the last decades. 25 years ago about 15 central power plants supplied the entire demand for electricity in Denmark (disregarding exchange with neighbor countries) whereas today the electricity is generated by numerous wind turbines and local power plants in addition to the conventional central plants. As a result of restructuring the electricity supply in Denmark wind turbines are now producing about 20 % of the electricity demand on average and Danish authorities are planning for 50 % in 2025.

One consequence of the increased share of wind power in electricity supply is that stable, controllable fossil plants are substituted by intermittent, largely incontrollable generating capacity, which does not hold the same capability to provide (mandatory) ancillary services. Along this line the US Department of Energy has estimated[1] that for every GW of wind power added to a system 17 MW spinning reserve must also be added to account for the system´s variability. In Denmark similar problems are foreseen and therefore an interest has emerged to clarify, which technologies could be suitable – technically and economically – for future provision of ancillary services in a Danish perspective.

The purpose of the present project was to evaluate and compare available options for dedicated electricity storage units to provide the mentioned types of short term system services in the Danish power system. The analysis was planned as a first phase in a two or three step procedure and aims to conclude with recommendations for a second project phase, where one or two small demonstration electricity storage systems can be installed to obtain own hands-on experience and contribute to a solid foundation for future decisions of considerable economic significance.

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[1] D. Link and C. Wheelock, Energy Storage Systems, Pike Research, 2010

2. Identification and selection of benchmarking methods

The present section briefly describes the types of ancillary presently purchased in the Danish power system. Based on this information the document identifies the benchmarking principles which have been used in the present ForskEl project “Electricity Storage Technologies for Short Term Power System Services at Transmission Level” (ForskEl project number 10426) for evaluation of potentially applicable storage technologies.

2.1 Ancillary Services in the Danish Power System Today

Presently, Energinet.dk buys the following ancillary services:

DK1 – West Denmark	DK2 – East Denmark
• Primary reserves • Secondary reserves (LFC) • Manual regulating reserves • Black start services • Short circuit power, reactive power and voltage control	• Frequency controlled normal operation reserve • Frequency controlled disturbance reserve • Manual regulating reserves • Black start services • Short circuit power, reactive power and voltage control

The technical specifications for the different services differ between western and eastern Denmark, since the two regions are connected to different regions of the ENTSO E system (the continental Western Europe and the Nordic group, respectively).

The primary reserve in DK1 is controlled by the frequency of the system and must be delivered within few seconds (<30 seconds). The size of the Danish reserves is determined from a national proportion of the required total reserve in the frequency region. Presently, about ±26MW is needed.

The secondary reserve in DK1 ensures re-establishment of the primary reserve and the (close to) real time balance of power flow over the borders. The reserve must be delivered within 15 min. About ±90MW are presently needed in order to ensure the balance..

Frequency controlled normal operation reserve in DK2 is controlled by the frequency and must be delivered (linearly) within 150 seconds. Presently about ±23MW is needed.

Frequency controlled disturbance reserve in DK2 is controlled by the frequency and must be delivered within 30 seconds. Presently about +175MW is needed

The manual regulating reserve (in DK1 and DK2) is a part of the regulating power that adjusts for the unplanned changes in production and consumption on the 15 minutes timescale. The power delivered through the market for manual regulation varies strongly, but the average power is about 200MW.

Black start services are required to restore the grid in cases of blackout. Black start service for HVDC lines can be provided by a diesel generator feeding auxiliary power or alternatively from a local storage device.

Short circuit power, reactive power and voltage control secure stable and safe operation of the power system. The services are delivered on transmission level by central power plants. Short circuit power is required to secure adequate function of HVDC connections, protection of relays and switches in the transmission grid. Reactive power and voltage regulation is required to control desired voltage at points in the transmission grid.

More details on these services and terms of delivery can be found in “Systemydelser til levering i Danmark – Udbudsbetingelser”, Energinet.dk, 8. juli 2009 (Dok. 9855/09 v3, Sag 08/1079).

2.2 Future Market Structures and Needs for Fast Reserves

Since the liberalization of the power market, there has been a general tendency that a still larger fraction of the power trade is cleared on markets still closer to real time. The intra-day markets have grown and today parts of the regulation services are also determined by market clearance few hours – or less – before the service is delivered. This tendency is likely to continue and it can be expected that most (if not all) of the ancillary services will be traded within hours of the time of delivery or shorter.

The quantitative needs for primary (frequency stabilizing) reserves are not expected to grow significantly in the future. In the continental European frequency zone the maximum instantaneous power deviation from balance is defined to be 3000 MW, based on operational characteristics concerning system reliability and size of loads and generation units. Since the size of the largest power plants or load units are not expected to grow significantly, the maximum instantaneous power deviation is not expected to grow and therefore the need for primary reserves will not increase. However, a consequence of increased wind power penetration could be needs for non-thermal fast reserves. Today the major part of Danish fast reserves (applicable in less than 30 seconds) are provided by thermal power plants, e.g. by throttling steam valves or changing power between preheating of feed water and steam generation (although in DK1 – Western Denmark – an increasing share of fast reserves is supplied by decentralized plants like gas and diesel engines). During periods with high wind power production it may become viable to shut these central plants down, and consequently the associated fast reserves will be unavailable and other technologies (like storage systems) will have to take over.

Another foreseeable consequence of an increase in the less predictable power generation (primarily from wind and solar power) is a significant increase in the needs for reserves on slightly longer time scales (from minutes to about one hour). For example, the need for secondary reserves ensuring stable exchange of electrical energy in accordance with agreements will increase with the wind power penetration as a consequence of the uncertainty in prediction of the power production from the large wind farms. A present example illustrating this problem is the balance over the Danish-German border. Sample data for this exchange of electricity is shown in Figure 2.1 below.

2.3 Description of Grid Functions Relevant for Electricity Storage Systems

This section briefly describes a number of functions that electricity storage systems should provide in the future. The functions are identified by Energinet.dk (at a joint meeting 8 March 2010) as important functions in the future grid and are listed below in prioritized order. The grid functions will be used to illustrate and evaluate the electricity storage capabilities.

1) Power balance on a future real-time market

It is expected that the markets for balancing production and consumption in the future will operate closer to real time and with shorter time steps, perhaps as short as 5 seconds. The ability to deliver power balance with short notice will on such markets have a large value and the technologies in the present project will be evaluated on their ability to supply (or consume) power within few seconds. Note, that the production (or consumption) will in this case not be controlled by frequency. Since these markets are not present, a quantitative assessment of the capabilities of a technology will be applied. An energy storage technology can operate either alone on the market or in combination with large production units improving their possible revenues by optimizing production at a given point in time.

2) Balance of power-flow to neighbor countries

Today the LFC reserve in west Denmark (DK1) ensures balance (i.e. power flow according to planned values) over the Danish-German border on the 10-15 minutes timescales. The imbalances occur, when the production and/or consumption (defined at the day ahead and hourly markets) differ from the planned production/consumption. Powers of up to ±90MW are today traded at this market. As wind power production increases, the uncertainty in the power production (within the 15 minutes to 1 hour time frame) will increase which again leads to an increased need for this type of reserves. It could also be expected that similar reserves will be needed in the eastern part of Denmark in the future.

3) Primary reserve

Today on the order of ±26MW of primary (frequency controlled) reserves are needed in west Denmark (+23MW in east). These numbers are the Danish “shares” of the required primary reserve in the two ENTSO-E regions (former UTCE and Nordel). The reserves are required to be activated within seconds and deliver linearly as function of the frequency deviation. The technical specifications are described in further details in “Systemydelser til levering i Danmark – Udbudsbetingelser”. In the present project the analyses are based on real data of frequency deviations from 50Hz to evaluate the requirements to a storage system (see Figures 2.3 and 2.4).

4) Black start of HVDC

The black start services in the Danish power system must be available for start up within 15 minutes and must be able to deliver continuous power for 8 hours. The total needs in Denmark are about 40 MW, which is today delivered primarily by gas turbines at central power plants. Due to the requirement of extended continuous delivery of power, several electricity storage systems are not immediately suitable for this type of service. However, electricity storage systems could be used to black start HVDC lines. The “old” technology HVDC lines require large short circuit power, while the new HVDC (+ or light) can use the DC side to start if the converter station is equipped with facilities for auxiliary power from inside the station.

Furthermore the classic (line-commutated thyristor-inverter) HVDC also needs continuous short circuit power (i.e. a quite stiff voltage source to operate against) during operation, e.g. a synchronous compensator. A system with a classic HVDC and a synchronous compensator in a black start situation is similar to the start up of a Load Commutated Inverter (LCI) drive. This could perhaps be done by (extended) HVDC inverter-control supplemented with, if needed, a 'small' AC-drive (with local power supply) to start up the compensator (motor start).

5) Voltage regulation

Voltage stability is ensured by a combination of activating the Automatic Voltage Regulators (AVR) on base-load power stations and switchable Capacitor Banks and Reactor Shunts strategically placed in the 400 and 150/132 kV grids. The inductive line losses make it inefficient to supply reactive power over long distances and voltage regulation is therefore done several places in the transmission system. Electricity storage can with the appropriate power electronics (or in combination with StatComs) provide reactive power and thereby stabilise voltage. The response time is crucial for this service. It is likely that the service of providing voltage regulation will be liberalized in the future power market. Except for one SVC installation in DK2 no facilities for electricity storage or StatComs are installed in Denmark, partly for price reasons.

6) Short circuit power

Short Circuit Power is provided on the high-voltage and middle-voltage grids by all synchronous generators in operation in any given situation i.e. central base-load power stations and dispersed CHP-plants. Furthermore Short Circuit Power is provided by two Synchronous Condensers owned by Energinet.dk and to a large extent from Energinet´s AC high-voltage interconnectors to Germany (DK-West) and Sweden (DK-East)

2.4 Benchmarking of Technologies

The exchange of power with neighbor countries (see point **2)** in Section 2.3 above) does not always follow the plans made ahead. Actually considerable deviations can be observed as reflected in Figure 2.1 below. It is seen from the figure, that the most frequent <u>deviation</u> is in the range og 30-40 MWh/h and that serious deviations occur quite often reaching deviations down to -300 MWh/h (lack of supply from Denmark compared to the plans) e.g. at hour 63. It is also seen that the deviations fluctuate relatively rapidly and it has been speculated if a business case will emerge in the future, where the value of fast response to the described deviations may increase considerably since the fluctuations may become increasingly unsatisfactory for seller as well as buyer.

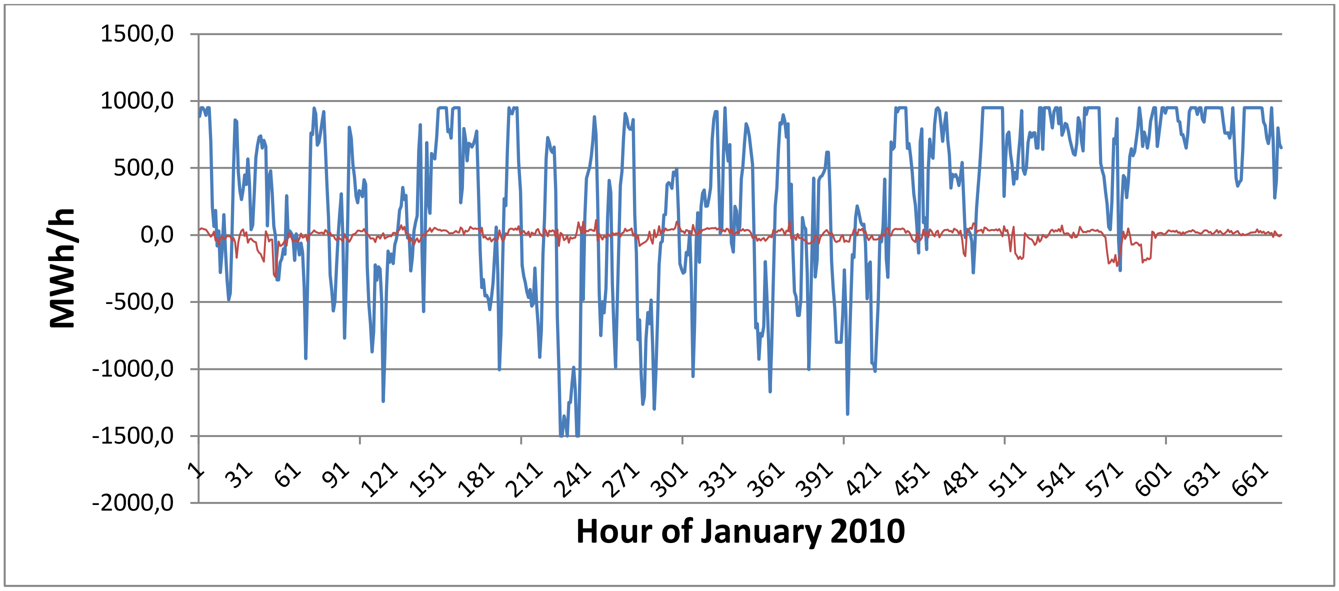

Figure 2.1. Power exchange between DK and D. The blue line shows the planned exchange of power in over the Danish-German border as a function of time in January 2010. The red line accordingly shows the difference between the actually measured and the planned exchange. Source of data: Energinet.dk

The data in Fig. 2.2 (source: Energinet.dk), which gives a picture of activated reserves during 24 hours in October 2008 (randomly selected), is used as a base line for the required call for activation of services the considered storage technologies should provide in the cases of the above listed issues 1)-3): Power balance on a future real-time market, Balance of power-flow to neighbour countries, and Primary reserve. Fig. 2.2 shows reversion of operational state for the energy store (loading or de-loading) approximately two times every hour and an average de-loading of 31% as well as an average loading of 20% relative to full capacity (actually bought capacity). Furthermore a complete up-activation as well as complete down-activation is seen approximately once every 2 or 3 hour.

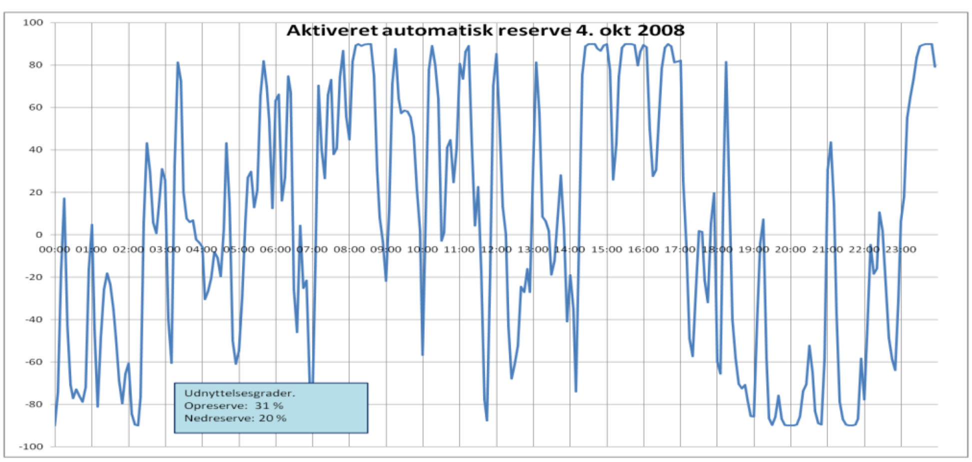

Figure 2.2. Activated automatic reserves in West Denmark 4 October 2008. The degree of utilization was for up-regulation 31% and for down-regulation 20%. (Source: Energinet.dk)

A more thorough analysis of frequency deviations has been done based on data received from Energinet.dk [2]. The data covers measured frequencies every second for the period 02-07-10 through 08-07-10 for DK1 and the period 04-06-10 through 20-06-10 for DK2. The data was analyzed for deviations exceeding limits relevant for activation of primary control reserves, frequency controlled normal operation reserves (FNR) and frequency controlled disturbance reserves (FDR), with respect to number and duration of events. The results are presented in Figure 2.3 for DK1 and 2.4 for DK2.

In DK1 primary reserves are activated in the range of deviations up to +/- 200 mHz from 50 Hz and a dead band of +/- 20 mHz is acceptable. The reserve must be delivered linearly proportional to the deviation in the range 20-200 mHz. The first half of the capacity must at minimum be delivered within 15 sec and the capacity must be fully deployed within 30 sec at deviations +/- 200 mHz. It can be seen from Figure 2.3 that <u>typically deviations exceeding 20 mHz have durations between 10 and 100 sec</u>. Only in relatively few cases durations exceed 100 sec and a maximum duration of approx. 1000 sec is found for both + and – 20 mHz. For this set of data the frequency deviations did not reach 200 mHz and only in very few cases did the deviation exceed 100 mHz (20 events for the entire period).

In DK2 FNR are activated upon frequency deviations in the range 49.9 – 50.1 Hz. A dead band is not accepted, but the sensitivity of frequency measurement is not required to be better than +/- 10 mHz. It is seen from Figure 2.3 that the <u>typical duration of deviations exceeding 5 mHz is in the range between 10 and 100 sec</u> and only few exceed 100 sec. Duration in the vicinity of 1000 sec is found as a maximum.

In DK2 FDR are activated when the frequency falls below 49.9 Hz and the response must be delivered inversely proportional to the frequency in the range 49.9 – 49.5 Hz. 50% of the response must be delivered within 5 sec and the remaining 50% within further 25 sec. Figure 2.4 shows that frequency deviations exceeded 100 mHz in many cases during the considered period and that the <u>typical duration is about 20 sec.</u>

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[2] Private communication with Kaj Christensen, Energinet.dk,, E-mails 9-7-10 and 14-7-10

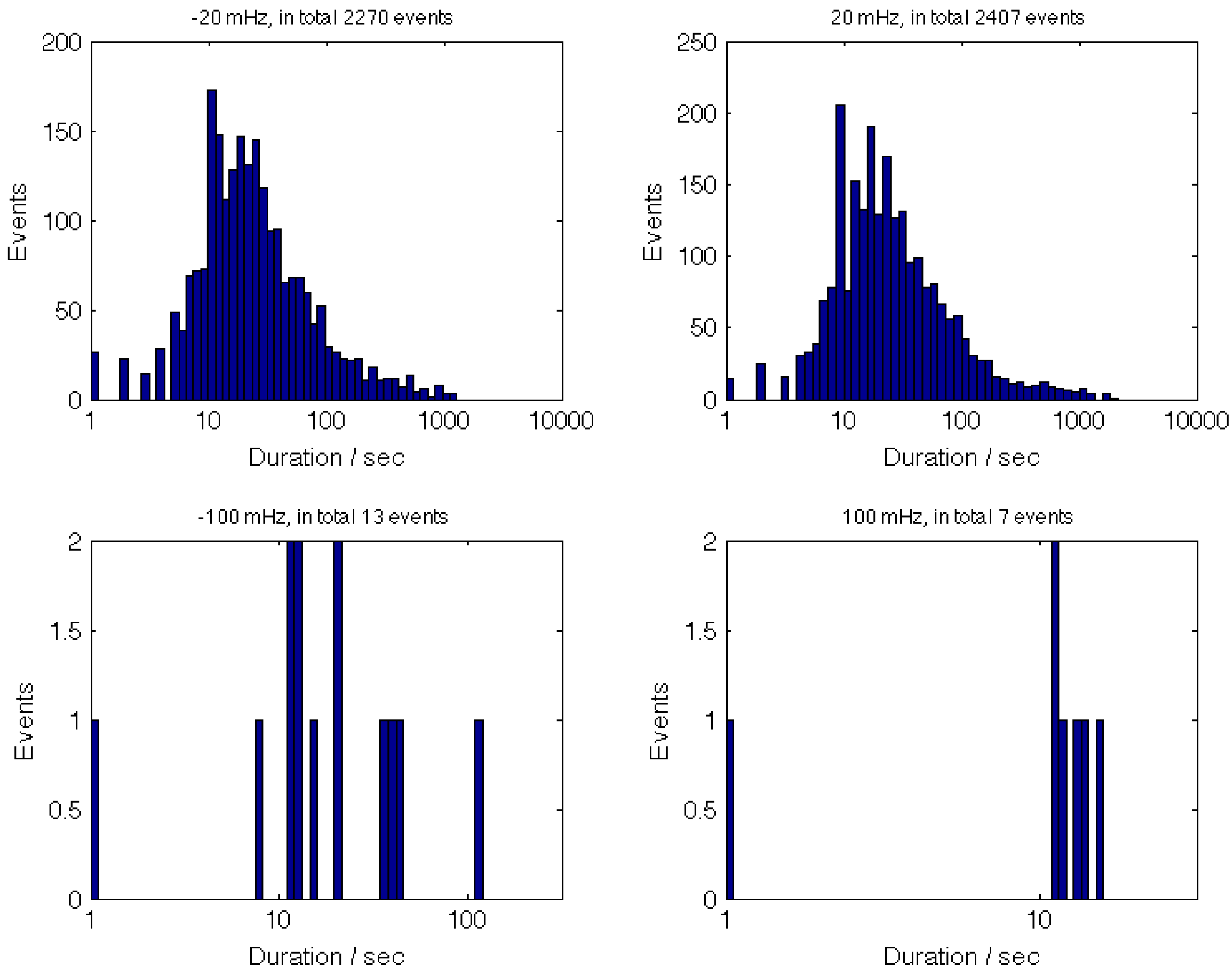

Figure 2.3. Statistical representation of frequency deviations from 50 Hz in DK1 for the period 02-07-10 through 08-07-10. The figure shows number of events where the deviation exceeded the indicated (above each graph) limits distributed on duration classes. The average frequencies of events are as follows: -20 mHz once every 266 sec, +20 mHz every 251 sec

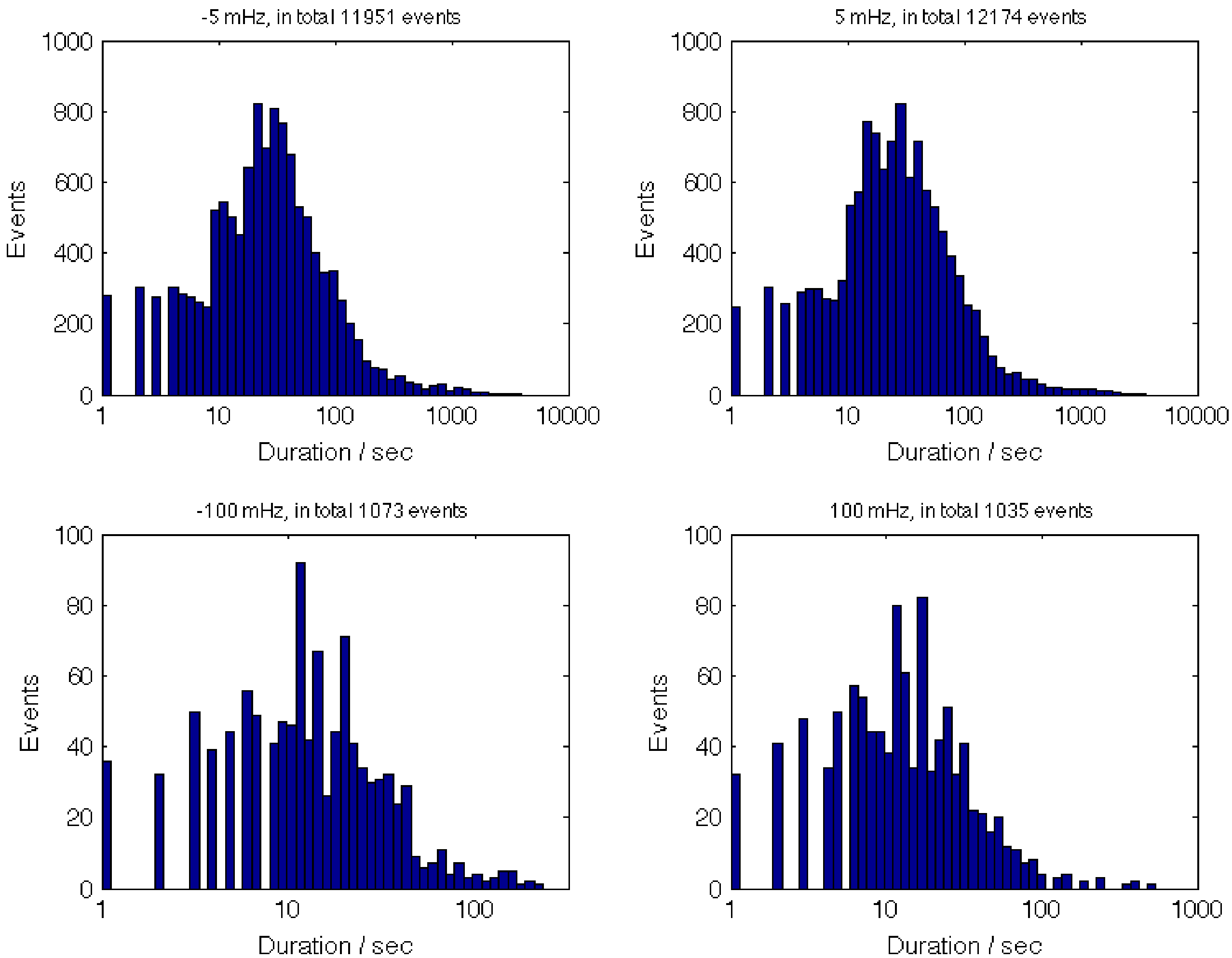

Figure 2.4. Statistical representation of frequency deviations from 50 Hz in DK2 for the period 04-06-10 through 20-06-10. The figure shows number of events where the deviation exceeded the indicated (above each graph) limits distributed on duration classes. The average frequencies of events are as follows: -5 mHz once every 117 sec, +5mHz every 115 sec, -100 mHz every 22 min, +100 mHz every 23 min.

The different technologies (batteries, CAES, fly wheels, hydro power, super capacitors and a few selected other technologies) are benchmarked according to a number of technical and economic benchmarking parameters. The technical benchmark parameters are:

1. start up time/ response time
2. ramp time
3. cyclability (based on the needs extracted from the above figures) and influence on lifetime
4. round cycle efficiency (electricity out over electricity in)

5. power capacity
6. energy capacity

From these parameters and from applying the grid function time series described above, the suitability of the technologies to provide the functions is evaluated.

In addition, the following economic benchmark parameters are taken into account:

1. investment price
2. operation and maintenance
3. expected lifetime

Combining the economic and technical benchmarks for each of the technologies allows an evaluation of the technologies with respect to short term power system services in the Danish transmission system.

3. Technologies

3.1 Batteries

Storage properties

Rechargeable batteries are very suitable for electrical storage, as the energy stored is not converted into mechanical energy, giving a simple system with no moving parts. This also yields a good round-trip efficiency. Batteries themselves do not give any limitations on response time, meaning that the battery can be discharged and recharged instantaneously. Properties like ramp time and frequency response are limited only by the pre-programmed grid response characteristics of the power electronics module. Due to the internal double layer capacitor in most batteries, the batteries may be ‘overloaded’ for a short period of time (few seconds). Power density of the battery pack is limited by the internal resistance of the battery pack, as higher currents leads to higher internal heating of the battery pack – which can lead to degradation and ultimately destruction of the battery cell. Energy content of the battery storage usually has a linear correlation between energy content and physically size/weight of the battery and cost, as long as you design within the same technology. If, on the other hand, the energy content is changed towards a very large storage system, it may be feasible to reconsider the selected battery technology. It that case, the correlation between size, weight and cost will follow the trend of the selected technology.

Working principle

In general there are 2 principles for rechargeable batteries – types that rely mainly on electrochemical reactions on the anode/cathode side during charge/discharge and the ‘rocking chair’ principle, where typically lithium ions move between anode/cathode materials.

Electrochemical batteries: For the current project, 2 types of electro chemical battery technologies are evaluated, lead-acid and sodium-nickel-chloride. These battery types are characterized by a creation and breaking of chemical bonds when the ions move between anode and cathode side of the battery. E.g. in a sodium-nickel-chloride battery the sodium reacts with chloride on the cathode side to form $NaCl$

Rocking chair batteries: The rocking chair principle mainly depends on a reversible intercalation of lithium in the anode/cathode materials, which makes the system a closed system. The relative concentration of lithium inside the anode/cathode material changes as a function of state of charge. The anode and cathode materials are separated by a porous membrane separator doped with an ion-conducting liquid and an organic solvent. During charging of the battery, electrons are moved from the cathode to the anode, which makes the lithium-ions move from the cathode to the anode also. During discharge, the reverse process takes place.

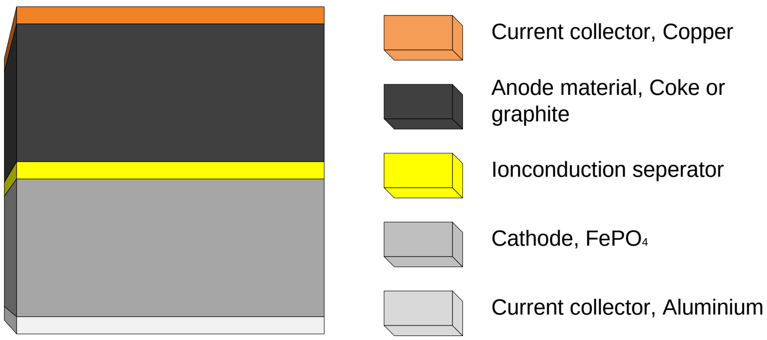

Figure 3.1.1: Schematic of layers in lithium ion battery

Different vendors use different materials for cathode, anode and electrolyte, on the international scene the competition is racing to develop the best material at the lowest cost. Some vendors (like A123) use special treatment of the cathode material to improve specific power of the battery cells. Others (like Electrovaya) focus on high energy density by maximizing the amount of lithium able to move between the anode and cathode. AltairNano uses different material for the anode, which enables probably the longest lifetime in the market, but at the cost of energy density. Care must be taken when choosing battery vendors, as it requires a good knowledge to the usage pattern of the battery pack and the pros and cons of each battery technology.

Technology description

Lithium-ion batteries

Electrical efficiency

Lithium ion batteries are the most efficient batteries from an electrical point of view, because the internal resistance of the individual cells is very low. A typical A123 2,3 Ah battery cell has an internal resistance of 0,01 Ω, which gives a internal loss of 0,2 Wh during a 15 minute, 7,1 Wh discharge, a roundtrip efficiency of 94% . The large active material area of a typical lithium-ion cell is the reason for the good electrical conductivity.

The charge retention of a lithium-ion battery is typical limited by 2 factors – the battery management system[3] and the internal short circuit of the individual cells. Typical the loss of a complete lithium-ion battery system is below 1% SoC / month, however highly dependent on the BMS implementation.

Degradation

Battery degradation follows from use and storage of the battery. Degradation can be described as 2 major degradation mechanisms seen on the electrical performance of the cell:

Power fade: The internal resistance of the battery, primarily the separator and anode interface (SEI[4] layer), increases over time. This increased internal electrical resistance leads to a loss of efficiency that increases the operating temperature of the battery cell. The main reason for the increased

[3] Battery Management System = BMS
[4] SEI = Solid Electrolyte Interface

resistance is the built up of the SEI on the separator surface[5]. This degradation mechanics is accelerated by high temperatures and high state of charge[6].

Capacity fade: During charge and discharge of the battery cells, material stress in the cathode and anode material causes the number of available lithium sites inside the material to be reduced, some lithium-ions are also 'trapped' inside the possible sites in the anode/cathode material, decreasing the number of available lithium-ions and hence the electrical capacity of the battery cell. Also the electrolyte reacts with some of the lithium, hence reducing the available lithium. This failure mechanism increases as function of $\sum\Delta DoD$[7], high temperatures and shelf time.[8]

Environment, resources and recycling

Lithium-ion batteries can be recycled, but the cost is high compared to the raw material cost. Several methods for reusing the precious metals exists, but with limited availability. The resource situation on the planet makes the presence of Cobalt in the cathode material an expensive solution over time. Lithium itself is not in short supply, but the price of excavating Lithium will rise in the future, as more energy and cost intensive mining operations will start.

Highlights

Lithium-ion batteries can be highlighted for their superior specific power even under sustained high C-rates. The technology is costly for bulk storage, but as the analysis will show later, the technology is well suited for ancillary grid service.

Lead-acid batteries

The lead acid battery type has been used in the industry for decades, and is a very well-known technology. It does have its drawbacks due to high weight and limited cyclability.

The lead-acid battery consists of two plates; the cathode plate, which is a lead alloy (Pb) and the anode plate which consists of PbO_2. The electrolyte used in the battery is sulphoric acid (H_2SO_4).

Electrical efficiency

The cycle efficiency of the battery lie on approximately 85 %, and is varies depending on the C-rate and DOD due to the high resistance of Lead-acid batteries.

The Lead-acid batteries have a rather high self discharge of 3% that in time will drain the battery if not in use.

Degradation

In lead-acid batteries the most important degradation mechanisms are the following[9]:

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[5] A. P. Schmidt et al / Journal of Power Sources195 (2010) 7634-7638
[6] High cell voltages
[7] Integration of discharge cycles, in other words, the integration of Ah drawn from the battery
[8] J. Wetter et al / Journal of Power Sources 147 (2005) 269-281
[9] Journal of Power Sources 127 (2004) 33-44

- Breakdown of anode and cathode plates, especially deep cycles has a deteriorating effect on the anode plate
- The active mass is broken down and looses connection to the current collecting grid
- Irreversible formation of lead-sulfate in the active mass
- Short circuits

The aging mechanisms are often dependent of each other. For instance corrosion of the grids will lead to higher electrical resistance which again will lead to sulfating.

Environment, resources and recycling

Lead-acid batteries can be recycled. The batteries are emptied for electrolyte, which is neutralized, and the rest of the battery is demolished and heated. This result in a burn of the organic materials and the lead can be refurnished and reused. The process is taken care of at specialized recycling facilities.

Highlights

Lead acid batteries should never be used 100% of the stapled capacity. A maximum of 75% DoD is typically recommended. For long lasting batteries, the DOD is limited to 30-60%, as both deep cycles and small cycles have a substantial deteriorating effect on the battery.

Non-sealed lead-acid batteries need some extent of maintenance, since they need to be refilled with water due to electrolysis of water during charging and due to evaporation of water to the environment.

The efficiency of the lead-acid batteries lies somewhat lower than that of lithium-Ion batteries.

Sodium-Nickel-Chlor batteries

The Sodium Nickel Chlor battery is also often called salt battery due to the content of Sodium and Chlor, like in regular cooking salt. The battery consists of 2 current collectors, anode/cathode and electrolyte. When the battery is heated to 270-350 °C, the electrolyte becomes liquid and can conduct the electrical charge carrying Sodium ions. The electrolyte is also electronically insulating. The Sodium is absorbed in either the Nickel-salt cathode or in the anode which consists of free Sodium. Due to the limited ion-carrying capability of the electrolyte, the battery is also not suited for high-power applications, but is better suited for high energy applications.

Electrical efficiency

The efficiency in continuous use is slightly lower than the other batteries at approximately 85 %, but in order to maintain the high operating temperature and to heat the battery it needs a heating system and insulation. Hereby the energy needed to heat the battery can be lowered. In order to maintain the high temperature of the battery it takes approximately 5W/kWh installed battery. If the battery is left not connected to the electrical grid, the battery will utilize its own energy to maintain the operating temperature; hence the battery will be depleted of energy after about 8 days. If the battery is cooled down, it takes 1-2 days in order to heat up the battery again. This substantial energy loss means that the Sodium-Nickel-Chlor battery is well suited for numerous circulation and continuous charge and discharge. When in use, the battery generates heat internally, it that case, the internal temperature needs conditioning, so the battery operate within its nominal parameters.

Degradation

The critical component in the Sodium Nickel Chlor battery is the ceramic separator, in which cracks can occur of either mechanical (vibrations) or thermal reasons (heating and cooling of the battery). In case of small cracks or holes in the separator, the battery will seal the hole itself, since the sodium from the anode reacts with the electrolyte and collects salt and aluminum in the hole. In the case of larger cracks, the battery can become short circuited, and the battery will no longer contribute to the capacity of the battery pack. But there is no substantial risk involved with the use of the battery, like thermal runaway or strong acid electrolyte.

Environment, resources and recycling

Except for a small amount of nickel in the cathode material, the battery consists of relatively noncritical elements. It can also be recycles and used in the melting process for the production of stainless steel[10], so the recycling capacity is substantial.

Highlights

Because of the high temperature of the battery the surrounding temperature has little effect on the performance. There is no memory-effect or the like, so the battery can be partially charged/discharge. The big hurdle is the high consumption of energy in order to maintain the high operation temperature and the limited cycle life.

Technology supplier – batteries

For the battery vendor benchmark, a number of different companies have been approached, asking them to complete the below shown 'Request for Information' (RfI):

	Units	Please complete
Company & cell information		
0.1 Company		
0.2 Contact person		
0.3 Selected cell		
Technical benchmark – cell level		
1.1 Cyclability @ 70% DoD cycling	Cycles	
1.2 Cyclability @ 10% DoD cycling	Cycles	
1.3 Roundtrip energy efficiency @ 1C / 1C or specified	%	
1.4 Shelf life @ room temperature	Years	
1.5 Specific power	W/kg	
1.6 Specific energy	Wh/kg	
1.7 Power density	W/l	
1.8 Energy density	Wh/l	
1.9 Energy loss / month as function of SoC	%	

[10] http://eaaeurope.org/EVS20_Long_Beach_2003.pdf, page 7

1.10 Ramp time (if possible, please provide graph)	s	
1.11 Specific power for 30 seconds	W/kg	
1.12 Power density for 30 seconds	W/l	
Economical benchmark – complete battery installation		
2.1 Investment / MWh	$/MWh	
2.2 Investment / MW	$/MW	
2.3 Yearly operation and maintenance cost	$/MWh	

Figure 3.1.2: Request for information

For the full RFI – see Appendix A

The following companies were asked to complete the RFI:

Company:	**Response:**
BYD	Yes
FZ Sonick	Yes
Shin-Kobe	Yes
AltairNano	Yes
Xtreme power	None
A123	Yes
EIG Battery	No
Ener1	No – due to re-organizing
LiTec	No – due to re-organizing
Electrovaya	None

Figure 3.1.3: Battery vendor list

The companies that participated in this stage of the project are also some of the industrial leader within the field of battery based ancillary services. In the following each of the responding companies will be described and their technological track-record within the field will be described also. Later, the benchmark analysis of their answers will be presented.

A123

Company profile and technology differentiation

A123 is a relatively young company, founded in 2001. They produce and sell lithium-ion battery cells, integrated battery packs and modules. Their key technological advance is their proprietary cell material, giving very long lifetime and high power capacity compared to the average lithium-ion technology. Their cells are based on lithium-iron-phosphate, which is a well-know battery cathode chemistry within lithium-ion battery systems. The chemistry is characterized by a high cycle life and safer failure mechanisms compared to the commonly applied lithium-cobalt chemistry.

Figure 3.1.4: A123 standard cell

Track record within energy storage

Figure 3.1.5: From A123 Chile installation

A123 claims to have built more batteries for grid ancillary services than any other company. Currently their 'standard' system (named SGSS) consists of a 53 foot container being able to deliver or absorb 2 MW electrical power and 500 kWh of electrical storage capacity. Currently a total of 20 MW ancillary service systems are installed in Chile, New York and California. The largest installation in Chile is 12 MW and is operated by AES (Commissioned in November, 2009)[11]. Also a 2 MW system is installed nearby a California power plant to meet reserve requirements. During 'Storage Week 2010' there was a chance to talk with AES - who operate a couple of A123 storage systems - regarding the performance of the Chile system, and they were satisfied with the systems, and they expected to degrade the power output with about 25% over the lifetime of the system. The degradation rate is uncertain on the system level, as the system only has been operation for 1 year. AES Energy Storage has invested in further 44 MW electrical power of A123 SGSS, to be installed during 2011.

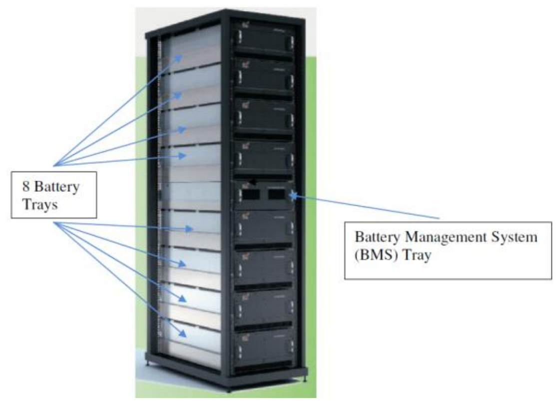

Figure 3.1.6: Suggested rack solution from A123

A123 expect to put about 60 MW of energy storage systems into operation during 2011, making them the largest supplier in the field of battery based ancillary service systems. Different configurations and scope of deliveries are possible, in the present project A123 suggested that they supplied batteries in the shape of a rack solution, containing 35 kWh of energy with a nominal voltage of 960V. The power output/input will be around 140 kW for 15 minutes.

AltairNano

Company profile and technology differentiation

Figure 3.1.7: AltairNano 50 Ah cell

AltairNano produce battery cells and battery modules. Their unique feature is the titanium-material used for anode material, which differ from common lithium-ion batteries that have carbon based anode material. AltairNano offer various cathode materials as well. Their cells operate at about ½ the cell voltage of an average lithium cells based on more common materials like graphite and cobalt-oxide. The key advantages of the choice of materials for the battery cells are the very long cycle life and very high electrical efficiency, but at the cost of energy density and power density.

[11] http://www.aes.com/pub-sites/sites/AES/content/live/0201399ac0f501240d3ca73100796a/1033/AES%20Energy%20Storage%20A123%20Gener%2018%20NOV%2009%20FINAL%20PDF.pdf

For a project regarding grid ancillary services, AltairNano proposal has special value, if the storage system does many small DoD[12] every day. In this case, the very long cycle life of the cells makes the initial, higher investment plausible. This should be compared to other battery technologies that possibly degrade too rapidly. In case of intense, small DoD variations, the total cost of ownership will be attractive – see next chapter for further analysis of the RFI specifications. The technology also offers wider operating ranges, especially in the freezing temperature range.

AltairNano offers a standard product ALTI-ESS of 1 MW / 250 kWh in a 53 foot shipping container, about ½ the energy and power density of e.g. A123 SGSS, which corresponds to the lower power and energy density of the battery cell themselves. For the current project, AltairNanos solution is the most significant competitor to the flywheel based solution, which also has a very long cycle-life. AltairNano´s solutions also offers balanced input/output characteristics, which means the system can either charge or discharge at the specified power level.

Track record within energy storage

2 MW was installed in PJM territory operated by Indianapolis Power & Light in May 2009[13]. According to the AltairNano[14], the batteries perform about 1000 small cycles per day, until now the degradation rate of the batteries is about 1% after 1 year of operation.

AltairNano offers for the FESTAS project a solution based on a modified IT rack system including battery management systems. They have also made indicative pricing for a turn-key system.

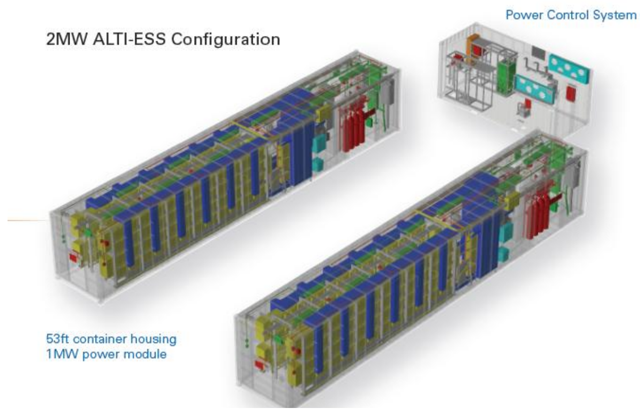

Figure 3.1.8: AltairNano ALTI-ESS product

BYD

Company profile and technology differentiation

Build Your Dream (BYD) is a China based cooperation, with a remarkable growth during the latest years. The produce and sell battery cells, modules and pack within their energy business. Their core technologies with the energy business are photo-voltaic, LED and batteries. They produce battery cells, modules and pack as well as entire energy storage installations. They also produce batteries for eg. Nokia and have developed their own electric car – the BYD e6.

Their main technological advance lays in their choice of materials for the cathode in the lithium-ion cell, which contains both cobalt and iron-phosphate, which gives the BYD cells less internal material

[12] Depth-of-Discharge

[13] http://b2icontent.irpass.cc/546%2F108842.pdf?AWSAccessKeyId=1Y51NDPSZK99KT3F8VG2&Expires=1282924294&Signature=mYHTlbM0ErHiudFsP0usjgtENs4%3D

[14] Private mail from Robert Misback, Senior director – Energy Storage, AltairNano

stress during charge/discharge cycling. This enhances the cycle life of the cell beyond the average lithium-ion cell.

Compared to the other lithium-ion manufacturers in the benchmark, BYD offers a remarkable low initial investment, but at higher running cost due to the cycle life of the batteries.

Track record within energy storage

BYD has developed a range of storage products 'Energy Storage System' (ESS), mainly for application in the Chinese market. Their main target is energy storage / load leveling, with an average runtime in hours.

Figure 3.1.9: BYD 800kWh / 200 kW container for bulk storage

BYD has a couple of energy storage installations, that provide both bulk storage and ancillary services, one installation is build into a container, containing 800 kWh / 200 kW, designed for bulk storage. They have about 6 MWh / 2,5 MW of energy storage in operation in China.

Reference list:

Power	**Energy**	**Date installed**	**Site**
1MW	4MWh	200907	BYD HQ
200kW	800kWh	200906	BYD HQ
100kW	80kWh	201004	China EPRI
100kW	80kWh	201005	Shanghai EPRI China
100kW	80kWh	201006	Nanjing Zhongsheng company
1MW	1MWH	201008	China national grid -Hebei province

Figure 3.1.10: BYD reference list

FZ Sonick

Company profile and technology differentiation

FZ Sonick SA is a co-operation between FIAMM and MES-DEA, making it possible to produce cells and modules. The technology is based on quite different materials, sodium-nickel-chloride being the cathode material. The operating temperature of the module must be above the melting point of Sodium; hence the module has excellent operating temperature range. Their standard module - denoted ZEBRA - has the following specifications:

Capacity	62 Ah
Energy Capacity	19,8 kWh
Operating voltage	206-348 V DC
Weight	201 kg
Thermal loss	<105 W
Peak current	224 A
Recommended discharge	C/2
Ambient temperature	-40 to 50 DEG

Figure 3.1.11: Typical module specification - FZ Sonick

As it can be seem from the specifications, the battery is not recommended for high power applications. The pricing of the module makes it relevant to consider a larger storage capacity to reach the requested power level. The technology is inheritably very suitable for bulk energy storage, as the cost per Wh is very competitive. The power density is considerably lower than eg. lithium-ion batteries, which makes the technology bulky. The limited cycle life also makes the technology less suitable for ancillary services, where the operation cycle will be characterized by many cycles, giving a high $\sum\Delta$DoD each day. The technology has many positive attributes, primarily low cost of cell material, plenty of material and easy recycling.

GE use FZ Sonick for sub-contractor regarding separator material and the BMI.

Track record within energy storage

Figure 3.1.12: Fleet project based on Zebra batteries

The Zebra battery has a long and well-known performance within transportation, amongst other the technology is used in the Norwegian Th!nk electrical car, the UK Modec commercial vehicle, as well as the technology has been used in numerous transport related demonstrations projects.

NGK Insulators

The Japanese company - NGK Insulators, Ltd. - also produces energy storage products, based on the sodium-sulphur technology. They were not part of the vendors approached within this project, but subsequently, the information public available has been evaluated. Their main reference list[15] consists of energy storage systems within of 2 application fields:

- System used for load leveling during day/night, often in combination with a substation that has reached its limit for power handling
- Power output smoothing from energy producing plants based on wind and sun. The systems are often located near the output of the power plant, and correct sudden change in production due to the fluctuating energy source

The company does highlight their systems ability to offer ancillary services, the services marked in green below.

		UK	Europe (UCTE)	USA
Immediate Response		Frequency Reserve	Primary Control	Regulation Control
	Response Time	Continuous	Continuous	Continuous
Fast Response		Fast Reserve	Secondary Control	Spinning Reserve
	Response Time	2 min	30 sec	10 min
Standby Reserve		Short-Term Operating Reserve	Tertiary Control	Non-Spinning Reserve
	Response Time	20-240 min	15 min	10 min

Figure 3.1.14: NGK Insulators business proposal with ancillary services[16]

Based on the principle and the energy to power ratio it is estimated that the technology offered by NGK Insulators will have the same technical characteristics[17] as FZ Sonick. Hence the technology is well suited for energy storage products, but less suited, if the focus is ancillary services.

[15] http://www.ngk.co.jp/english/products/power/nas/installation/index.html
[16] http://www.ngk.co.jp/english/products/power/nas/application/index.html
[17] http://www.ngk.co.jp/english/products/power/nas/principle/index.html

Shin-kobe

Company profile and technology differentiation

Shin-Kobe is an old company established in 1916 with currently 1150 employees, the company is part of a larger industrial group. Their main business areas are electric equipment, storage batteries and plastic products. They produce and sell battery cells and modules. Based on NEDO funds, they have developed a lead-acid battery with a high cycle life and very long shelf life for the technology. A big disadvantage is the low power density and that the battery cannot operate balanced, in this case, the battery can be discharged in 2½ hours, but needs 5 hours to charge.

Track record within energy storage

The lead acid battery technology of Shin-Kobe has been developed and put into service as output power stabilization systems for wind turbine parks. The batteries have demonstrated long operation time in numerous systems, 27 systems in 100+ kW range and 2 systems of 4.5 MW each. Some of the systems have been in operation for 10 years. All systems are bulk storage systems.

Benchmark analysis

The data obtained from the RFI has been analyzed, and will be examined in the following.

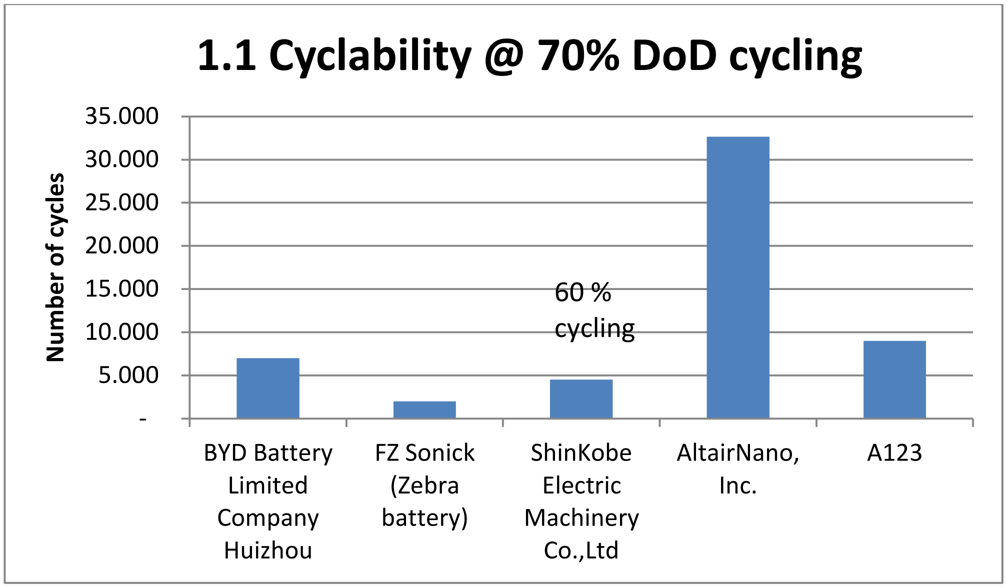

Figure 3.1.16: Number of cycles the battery is capable of with a SOC cycling of 70 %, e.g. from 15 to 85 % DOD. The data from ShinKobe is at 60 % cycling. The battery is considered exhausted, when the capacity is reduced to 80 % of initial capacity.

The number of 70 % DOD cycles vary very much depending on the battery type. The range is from 2000 cycles for the FZ Sonick battery until 32,000 for AltairNano. The data from ShinKobe is based on 60% DoD cycling, because a higher DoD will lead to quicker degradation for the lead-acid technology.

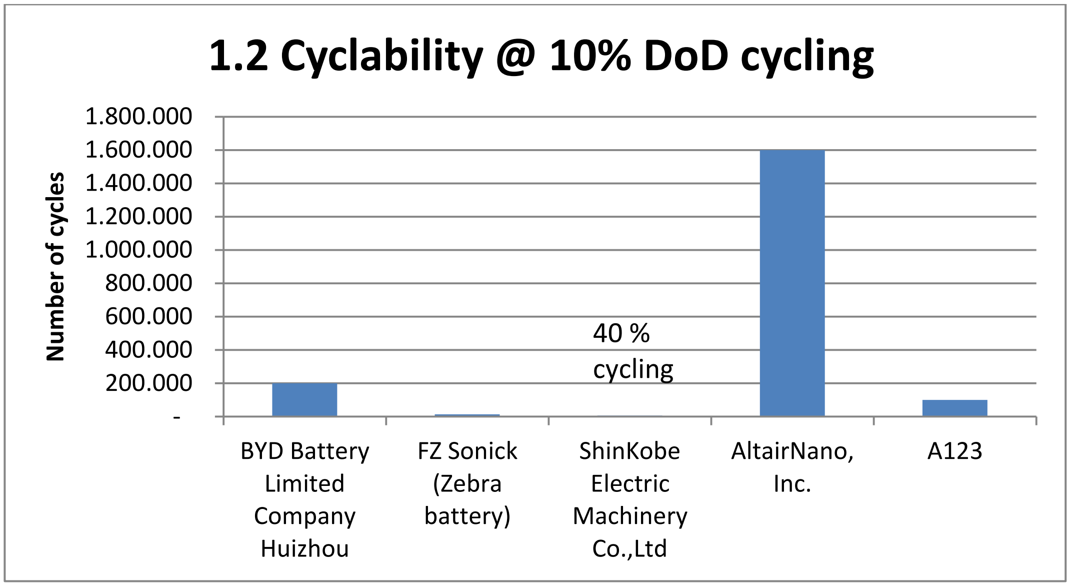

Figure 3.1.17: Number of cycles the battery is capable of with a SOC cycling of 10 %, eg from 70 to 80 % DOD. The data from ShinKobe is at 40 % cycling. The battery is considered exhausted, when the capacity is reduced to 80 % of initial capacity.

At 10 % DOD the number of cycles varies tremendously, from 6.000 cycles for the ShinKobe to 1.6 million for AltairNano. Coupled with the number of variations seen on the Danish electrical grid, it is clear that a number of technologies will degrade very rapidly given the operation conditions of an ancillary service system.

Overall the AltairNano has a very impressing number of cycles, FZ Sonisk and ShinKobe low numbers, and BYD and A123 lie in between. The data from Shinkobe is stated at 40 % SOC cycling. Low percentage cycling of the lead-acid batteries from ShinKobe can result in premature capacity loss, and should be avoided.

Generally the number of cycles are not a guaranteed figure in the specific application, and especially at the 10 %DOD cycling, it is probably also subject to an estimation. The very large differences in the numbers indicates though that you get far from the complete picture by only looking at the price, energy and power capacity of a battery.

The battery is not exhausted after the specified number of cycles, but the capacity is reduced to 80 % of the original.

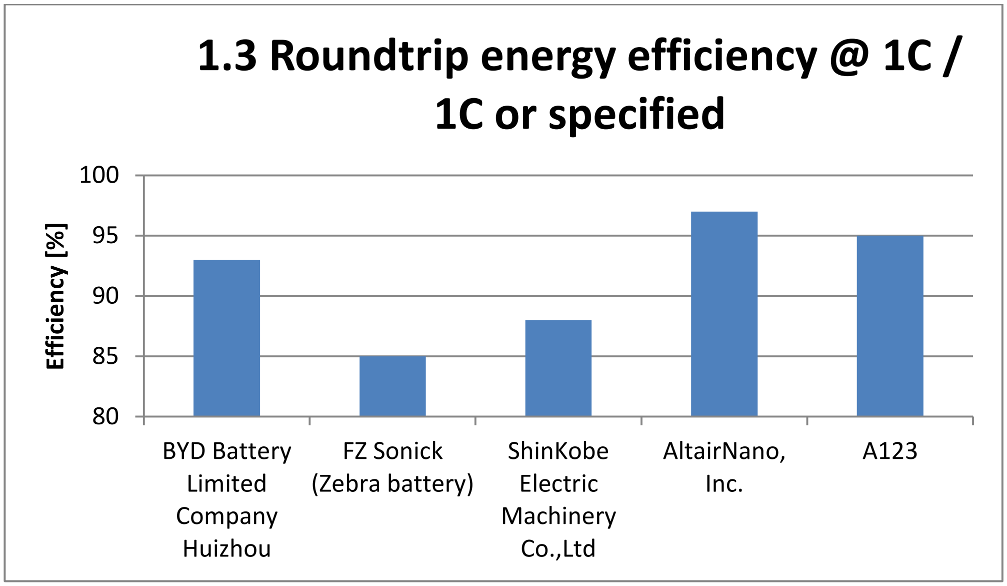

Figure 3.1.18: Roundtrip efficiency for charge and discharge of the battery at 1C discharge and 1C charge. Losses in power electronics module is not included. For Shinkobe the data is at 0.1 C/0.1 C, and for FZ Sonick at 1C discharge and 0.5 C charge.

The roundtrip efficiency of the batteries only lie in the range of 85-97 %, but is also depending on the discharge rate, especially high rates leads to bigger losses for the ShinKobe and FZ Sonick batteries due to high internal resistance. When considering complete systems, there are also some losses in power electronics converters, and some power use for thermal management like A/C and fans, notably is the fact that lower efficiency also leads to a higher need for cooling

The shelf life of all the battery types is 15-20 years. A system will probably be designed in order to have a lifetime of maximum 10 years. After that the batteries can be replaced by newer, better and less costly battery technologies. The shelf life is also an estimate, since the nature of the specification gives, that it takes a long time.

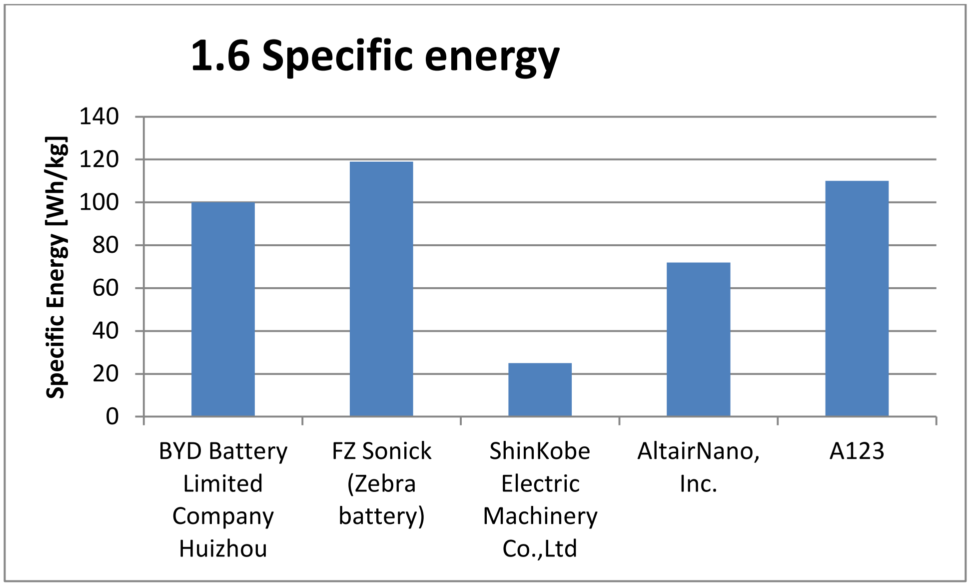

Figure 3.1.19: Specific energy content of the batteries. Where possible stated at a discharge rate of 1 C.

Regarding specific energy, ShinKobe is the most bulky system, whereas FZ Sonick has a high number of 120 Wh/kg. A123, BYD and AltairNano lie in between.

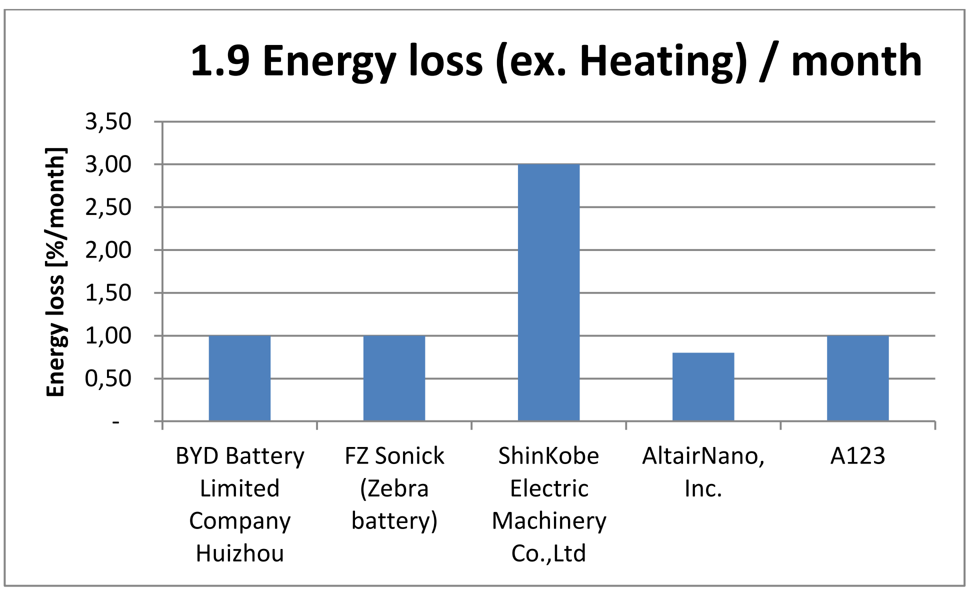

Figure 3.1.20: Energy loss when leaving the battery unused. Losses for maintaining a high temperature for the FZ sonick batteries is not included.

The energy loss from leaving the batteries unused are all below 1 % except for Shinkobe at 3 %. The loss from heating FZ Sonick battery is not included which can change the picture tremendously. If this type of battery is not used, the heatloss is approximately 5 W/kWh, which will drain a fully charged battery in only 8 days.

The ramp time for the batteries from 0-100 % all lie below 1 s, and is regarded sufficient for all grid services.

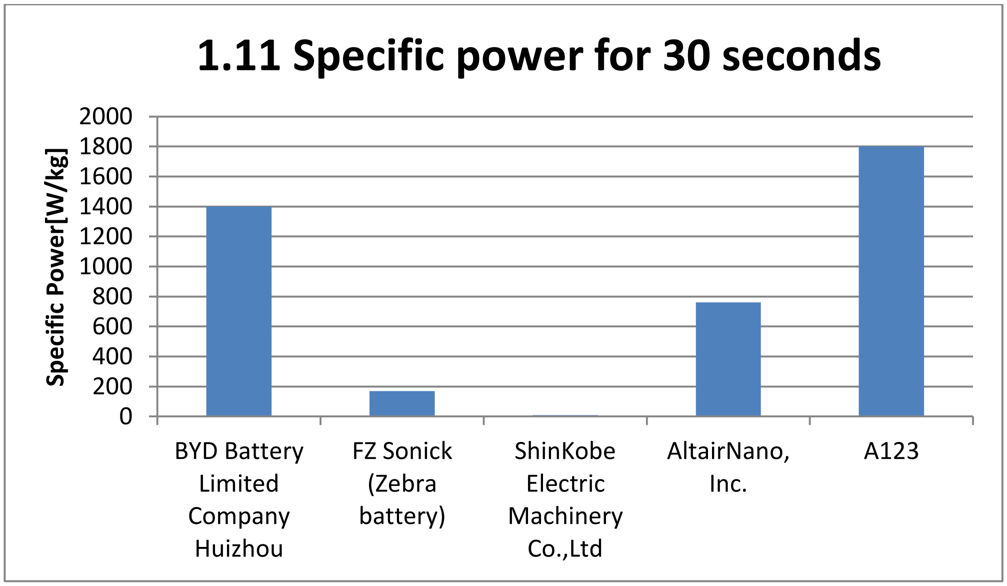

Figure 3.1.21: Possible power the battery can deliver continuous for 30 seconds.

The short term power from the battery is stated from 1800 W/kg for A123 until 10 W/kg for ShinKobe. For a shorter period of time, the power can be higher. In a system, this figure also depends on the power electronics, which typically will be designed to set the limitations.

The Specific power of the batteries is very different. Both weight and volume of the battery storage facility show the same overall tendency.

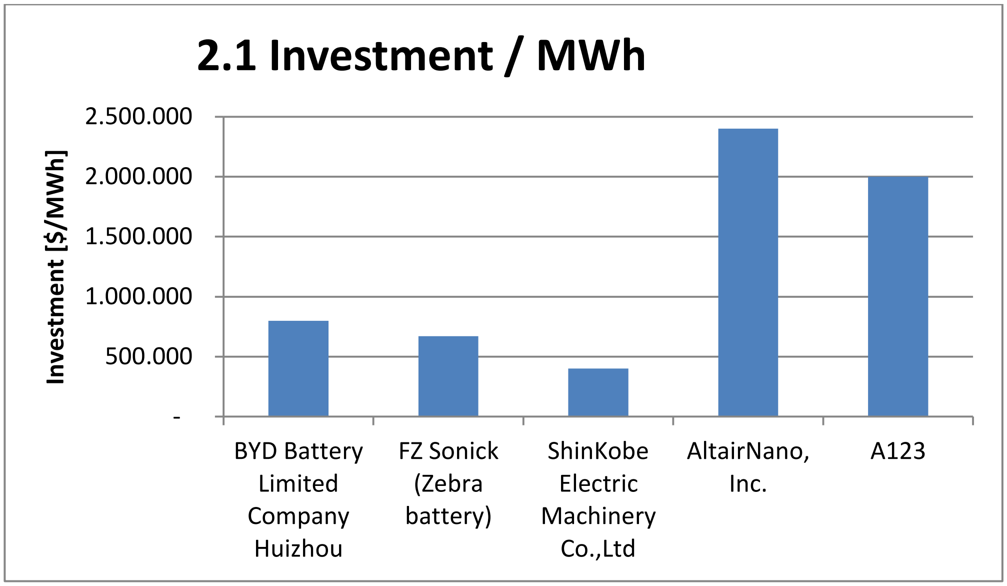

Figure 3.1.22: Initial investment for a battery storage per MWh.

AltairNano is the most expensive battery per energy content followed by A123. Low cost per MWh is offered by BYD, FZ Sonick and ShinKobe.

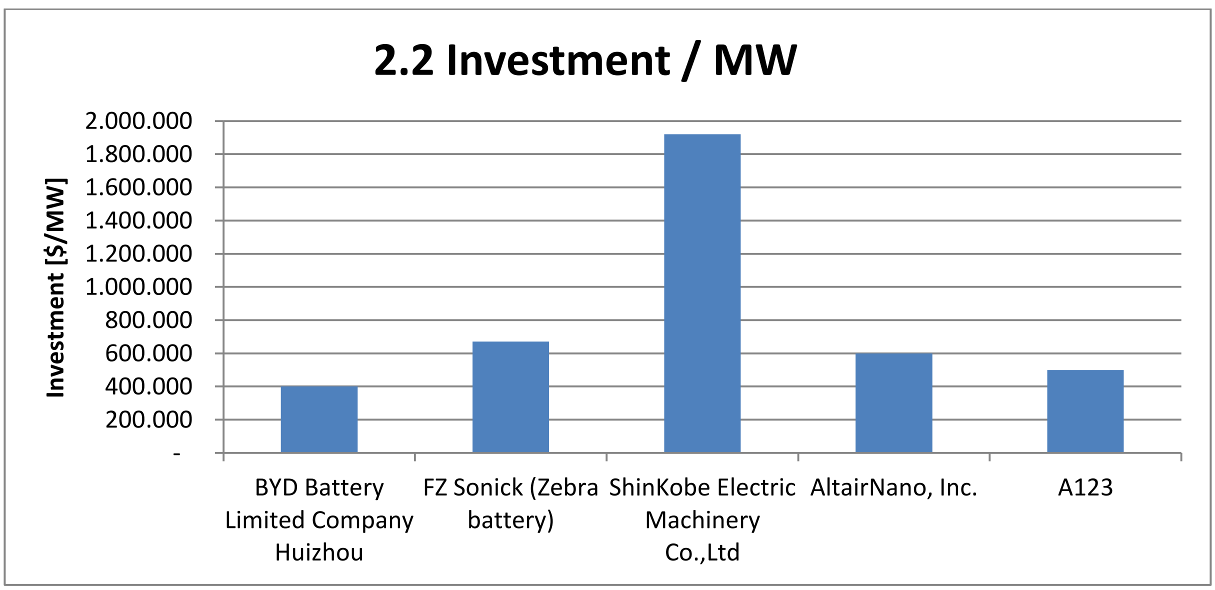

Figure 3.23: Initial investment for a battery storage per MW

When looking at the investment per MW, the picture changes much, since the less expensive batteries per MWh cannot deal with high discharge rates. The suppliers shift places, so AltairNano, BYD and A123 are the least expensive.

Based on the figures of cost, capacity and cyclability, the devaluation in terms of degradation can be calculated. The battery is considered exhausted when 80 % of the initial capacity remains. For the grid ancillary service application, it is possible to operate the system beyond the 80% remaining capacity; however the system should be degraded for power and energy.

A very simple model of the cost per MWh stored in the ancillary service system can be formulated like this:

$$Degradation\ cost = \frac{\text{Investment [\$/MWh]}}{\text{N}_{\text{Cycles}} * DOD} = \text{[\$/MWh]}$$

The full investment in battery bank is depreciated over the number of cycles the battery can perform, corrected by the stated depth of discharge. This simple model takes into account the limitations in lifecycle of the different battery technology and the different vendors.

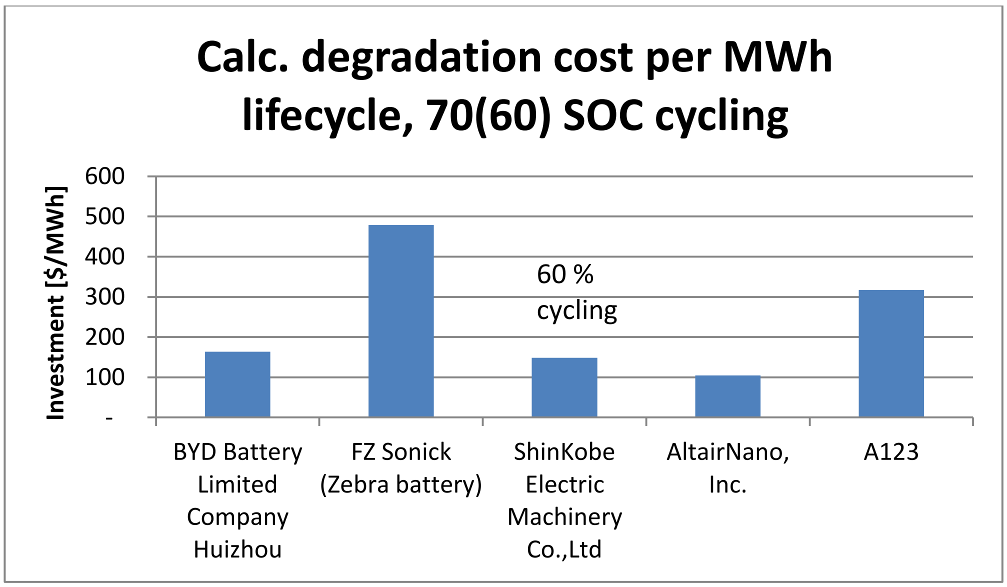

Figure 3.1.24: Degradation cost for the different battery suppliers. For ShinKobe, the data refers to 60 % SOC cycling, for the others 70 % cycling.

Despite the high initial expense for AltairNano, the long lifetime results in the lowest cost per MWh if seen over the life-cycle of the battery. A123 and FZ Sonick have the accumulated highest expense.

If is it assumed that the battery will experience many, smaller DoD cycles per day, the figure for 10% DoD cycle life can be utilized. Since the degradation of the battery is not only an integration of the number of Ah drawn from the battery, but also highly dependent of the DoD, the simple depreciation model can be utilized again and gives the following results:

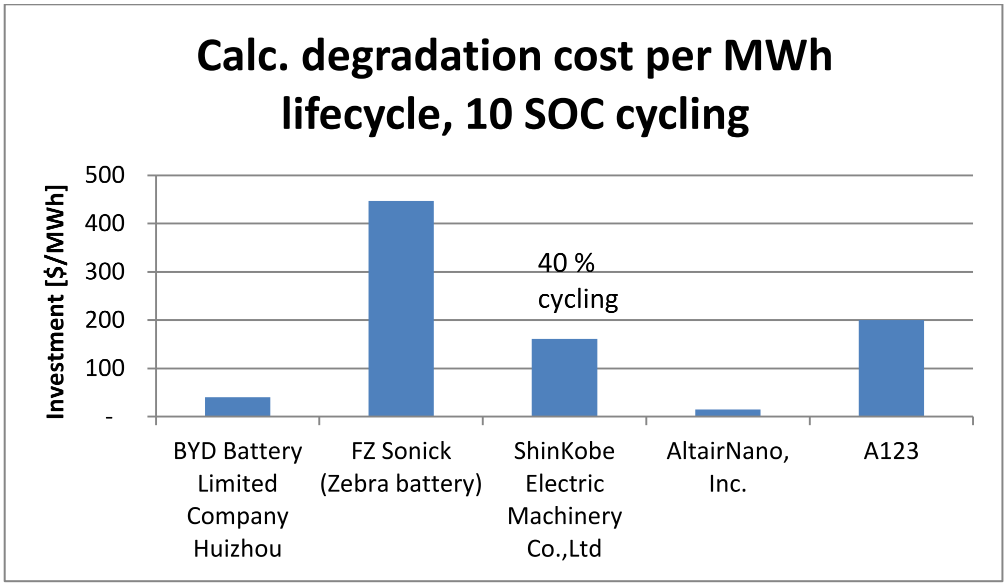

Figure 3.1.25: Degradation cost for the different battery suppliers. For ShinKobe, the data refers to 40 % SOC cycling, for the others 10 % cycling.

With the data from 10 % SOC cycling, the cost of storing a MWh becomes very low for AltairNano, due to the very high number of cycles the cells are stated to endure. The supplied lifetime data from BYD is subject to some questioning.

Conclusion

The current investigation has provided important data from various vendors and various battery technologies. It can be seen from the analysis that although lead-acid (Shin-Kobe) and sodium-nickel (FZ Sonick) batteries are the cheapest to invest in per MWh, they are not suitable for providing fast ancillary services, for 3 reasons[18]:

- Inherently, the 2 battery technologies provide a limited cycle life, which means that they degrade too quickly given the operation pattern of a fast ancillary service system
- The maximum recommended charge and discharge rate of the battery technology makes the system not suitable for fast ancillary service, as the limited charge/discharge rates makes the entire system bulky
- The limits in charge and discharge rate also makes the system very costly per MW, which can be seen from the analysis **Fejl! Henvisningskilde ikke fundet.**

The only battery technology found relevant for fast ancillary services is the lithium technology, which can be optimized for high charge/discharge rates, enabling a system to work balanced – this means a

[18] However, both technologies will be very relevant for small-size, bulk storage systems, with charge/discharge rates of hours and few charge/discharge cycles per day. Based on this operation profile, these battery technologies can be recommended.

system to import and export power with equal figures. There are, however, big differences in the initial investment stated by the 3 vendors (A123, AltairNano and BYD), to some point, the big differences in prices reflect different material cost in the battery.

If the cost/MWh is analyzed**Fejl! Henvisningskilde ikke fundet.**, the cheapest operation cost is clearly BYD at $163/MWh, this assumes that the operation profile will be characterized by longer, deeper discharge operation patterns (70% of energy drained from the storage system). This assumption is not entirely true, as the analysis of the historical data from the benchmark, states that the operation profile will be characterized by many events each day (300-700) with a short duration (most events are < 100 seconds).

Therefore it is more relevant to look close at the expected lifecycle based on a 10% energy drain, this is analyzed in Figure 3.1.**Fejl! Henvisningskilde ikke fundet.**, where the operation cost is lowest for AltairNano at $15/MWh. BYD offers storage cost at $40/MWh and A123 is the most expensive at $200/MWh. These number do have a certain degree of uncertainty, as the battery vendors not necessarily knows the exact cycle life at these discharge rates/DoD, and since the cycle life is quite high it takes long time to verify the degradation rate. Eg. AltairNano predicts a 1.600.000 cyclelife at 10% DoD, if this number should be verified in a laboratory, a 10% DoD cycle could be operated every 12 minutes, making it possible to perform 43.200 cycles/year, making the storage system to operate continuously for 37 years, before the typical 80% remaining capacity is reached and the battery has reached its end-of-life. However the relationship between DoD and cycle life is well described.

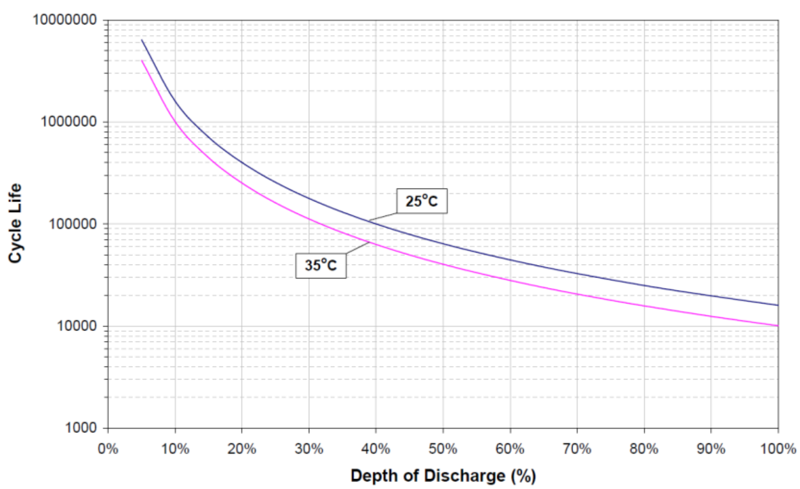

Figure 3.1.26: Predicted cyclelife until 80% remaining capacity - AltairNano

Recommendations for small scale battery system

If the provided data for frequency deviations are normalized for the western part of Denmark, the following number of events per day can be seen:

Region	Frequency deviation	Events/day
Eastern Denmark	+100 mHz	60
Eastern Denmark	+5 mHz	706
Eastern Denmark	-5 mHz	693
Eastern Denmark	-100 mHz	62
Western Denmark	*+100 mHz*	*1*
Western Denmark	*+20 mHz*	*344*
Western Denmark	*-20 mHz*	*324*
Western Denmark	*-100 mHz*	*2*

Figure 3.1.27: Event/day per region

If it is assumed that each 'event' lasts on average 100 seconds and the storage on average should export about 50% of nominal power, the average event will for the A123 and AltairNano cause a SoC change of 5,6 %. For the BYD system the corresponding SoC change would be 2,8 %. These assumptions leads to an average of 1,2 million events over a 10 year period with an average SoC change of 5,6 %.

Lithium ion batteries characteristics for the benchmarking

start up time/ response time	Much less than sec
ramp time	Unlimited
cyclability and influence on lifetime	Thousands for 70% DoD Millons for 10% DoD
round cycle efficiency (electricity out over electricity in)	High – up to 95%
power capacity	Full scalability
energy capacity	Full scalability
investment price per kW and kWh	About 400 EUR/kW and 1600 EUR/kWh
operation and maintenance price	Very low
expected lifetime	Years, depending on usage pattern

The AltairNano system has an estimated lifetime of 60 million 5% SoC cycles, making the system operational for 50 years. However, the shelf life[19] is stated to be 20 years – but this figure is also an estimate from the vendor.

[19] If stored, with no charging/discharging, the battery typically exhibit capacity fade, hence the shelf life is limited

In order to recommend a battery vendor, it is recommended to experimentally verify some of the degradation parameters and numbers, to find the suitable vendor. Based on the current available data, AltairNano seems to be too durable for the operation profile, while the figures stated from A123 and BYD is 100.000+ (A123) and 200.000 (BYD) at 10% DoD. BYD first claimed the cycle life to be 20.000, and when asked again, the number was changed to 200.000, so we estimate the number to be not-verified by the vendor. However, these cycle life numbers highly influence the initial investment and the operation cost of the system, therefore it is recommended to:

- Verify the degradation profile by a 3rd party, incl. Highly Accelerated Life Test, perhaps as a comparative setup between 2 or 3 vendors
- Establish a small-scale demo system, that operates grid connected, to clarify the operation profile

3.2 Compressed Air Energy Storage

Working principle

Compressed Air Energy Storage (CAES) is based on storing energy as potential energy in pressurized air.

When compressing gases (air) the pressure increase is accompanied by an increase in temperature. The temperature raise is highly depending on the pressure ratio (the ratio between out- and inlet pressure of the compressor) and the compressor outlet temperature has to be cooled before storing. When utilizing the stored energy by re-expansion, the heat has to be added again in order not get freezing.

Different technologies/concepts exist all based on CAES being at different stages of development:

1) Compressed air stored underground and combined with gas turbine
2) Compressed air stored over ground and combined with gas turbine
3) Compressed air stored underground incorporating heat storage (AACAES)

Compressed air stored underground and combined with gas turbine

Of the above mentioned it has only been possible to identify demonstration plants based on this type: Until now two full scale systems have been realized: The 290MW plant in Huntorf in Germany, which has been in operation since 1978, and the 110MW plant in McIntosh, Alabama, USA, which has been in operation since 1991.

This type of system is illustrated in Figure 3.2.1.

This system has a common compressor-motor/generator-expander train. The system can be considered as a traditional type gas turbine having the compressor (1) and turbine (3) separated by the motor/generator (2), connected by clutches making separated operation possible. Compared to a traditional gas turbine the operating pressure is much higher and multi stage compression having intercoolers are needed when charging the caverns (4). When discharging, the natural gas is heating the compressed air before expanding through the turbine (3) driving the generator (2) and delivering electrical power to the grid.

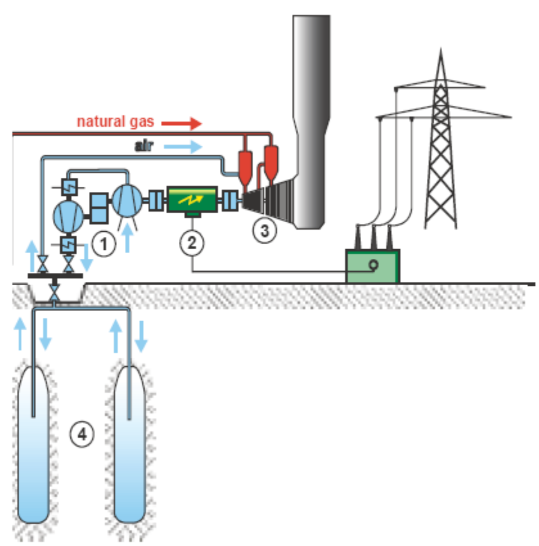

Figure 3.2.1 Schematic presentation of CAES having underground storage

Huntorf plant:

290 MW output
< 4hrs continuous operation
60 MW input
Output/input = 1/4
2 caverns (150 000m^3)
Round trip efficiency = 25%

McIntosh plant:

110 MW output
26 hrs continuous operation
60 MW input
Output/input = 1/1,7
1 cavern (540 000 m^3)
Round trip efficiency = 26%

It is not trivial to define the round trip efficiency of the electricity storage in these CAES plants because the electricity storage only accounts for a minor share of the energy input to the system. Defining the storage efficiency as electricity output divided by the sum of fuel and electricity input would be misleading as this would show efficiency higher than conventional gas turbines even though significant losses occur in throttling of the air from the cavern and cooling of the air to the cavern. Several definitions may be done. The above mentioned round trip efficiencies are based the fact that electricity is equivalent to the thermodynamic state variable exergy. Thus the exergetic efficiency of the three steps (compression, storage and expansion) multiplied is a reasonable measure for the efficiency of the storage. The efficiency values that result from this calculation are obviously very low and show that significant improvement of CAES technology is needed. Studies show that plants configured like the above mentioned can reach 40% efficiency.

Up to 20% load can be reached in 30 seconds and 3-30 minutes for full load (Energy Storage and Power Corporation).

A second generation version of the system is suggested by ES&P (Energy Storage and Power Corporation) based on standard gas turbines illustrated in Figure 3.2.2: Left: The air used for supercharging the burner chamber. Right: The cold exhaust air from the air expanders is replacing the ambient inlet air making the gas turbine running at much lower inlet temperature.

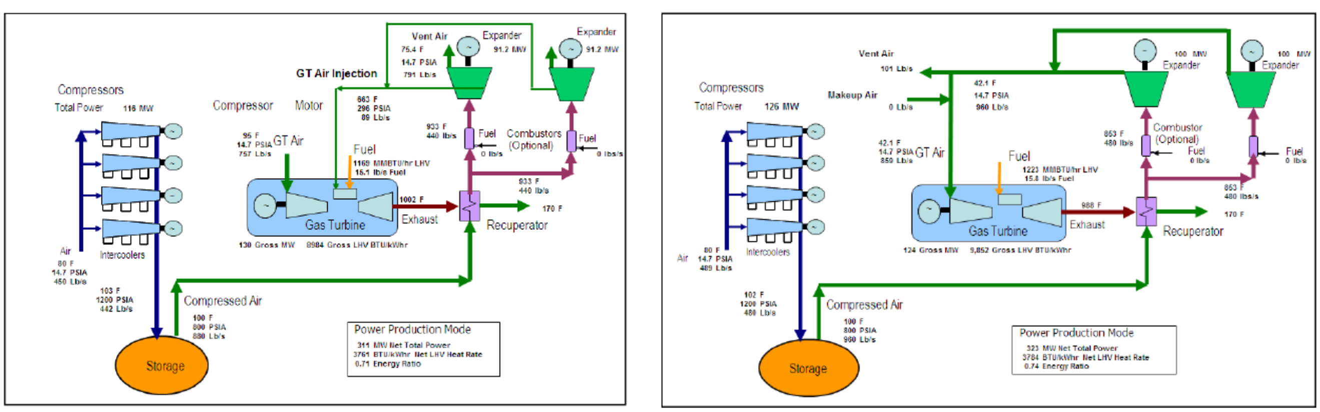

Figure 3.2.2 Second generation CAES by ES&P both using exhaust heat for partly reheating of the air before expanded in the air expanders. Separate compressor for charging.

The system is scalable from approx 15 to 600 MW, based on standard gas turbines. The air expanders are counting for up to 65% of the electrical power production. Approx 0.65 to 0.75 of the kWh input to the system is returned to the grid (ES&P), but as natural gas is consumed during the discharge this cannot be compared to round trip efficiency directly.

No systems have been demonstrated on this design.

Compressed air stored over ground and combined with gas turbine

ES&P has also carried out a detailed design of a 15 MW second generation CAES based on above ground storage in 8” (200mm) steel pipes shown in figure 3.2.3.

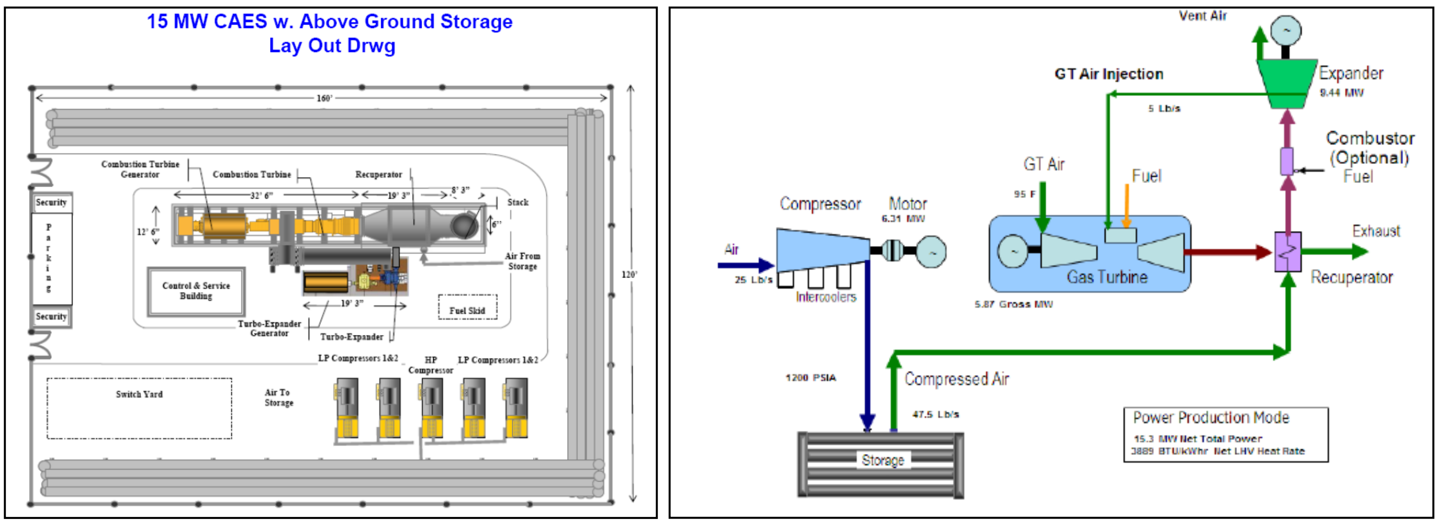

Figure 3.2.3 Schematic presentation of 2nd generation CAES having above ground storage

A detailed cost calculation on a 15MW system based on a 6MW gas turbine is available from ES&P and shown figure 3.2.4.

Summary Table of Performance Estimates (w/o specific optimization)

Description of Item	Air Injection	Inlet Cooling
Civil/Architecture		
Site, Clearing & Grubbing	60,000	60,000
Fence 440 LF w/2gates	6,600	6,600
Slab on Grade w/ 2' Haunches	80,750	80,750
Compressor Slabs (X4)	9,500	9,500
Control & Service Building	360,000	360,000
Sub-total	**516,850**	**516,850**
Equipment Costs		
Combustion Turbine	2,600,000	2,600,000
LP Air Compressor	1,400,000	1,400,000
HP Compressor	450,000	450,000
Heat Exchangers	950,000	950,000
HP Expander	484,000	1,000,000
LP Expander	727,000	-
Compressed air Storage	5,200,000	5,200,000
Sub-total	**11,811,000**	**11,600,000**
Mechanical (installation)		
Combustion Turbine	750,000	750,000
LP Air Compressor	150,000	150,000
HP Compressor	50,000	50,000
Heat Exchangers	225,000	225,000
HP Expander	125,000	300,000
LP Expander	250,000	-
8" Steel Pipe	30,000	30,000
Sub-total	**1,580,000**	**1,505,000**
Electrical and Controls		
Misc. Electrical	100,000	100,000
Field Mounted Instruments	150,000	150,000
Sub-total	**250,000**	**250,000**
Indirect Costs		
Engineering and Management	1,200,000	1,200,000
Start Up & Commissioning	100,000	100,000
Contingency	750,000	750,000
Construction Overhead etc.	750,000	750,000
EPC Contractor Profit	1,500,000	1,500,000
Licensing Fee	125,000	125,000
Sub-total	**4,425,000**	**4,425,000**
Total Capital Cost	**18,583,000**	**$18,297,000**

Figure 3.2.4 Cost calculation of 15 MW CAES having above ground storage

Compressed air stored underground incorporating heat storage (AACAES)

The above mentioned systems all need reheating of the air at discharge to compensate for the heat rejected when compressing the air at the charging.

The possibility of storing the heat from the compression before storing the air and then reuse it at discharge, is being investigated by a German consortium headed by RWE Power in the ADELE project. The system is illustrated in figure 3.2.5.

Personal communication with RWE has revealed that a full-scale plant in the range of 250MW at 4-8 hours full load (= 1 to 2 GWh energy stored) is being investigated and the price is expected to be "notable below 1000 EUR/kW", depending on cavern location and choice of compression train. The design goal is a round trip effiency of 70%.

A large demonstration plant is expected in operation in 2015-6.

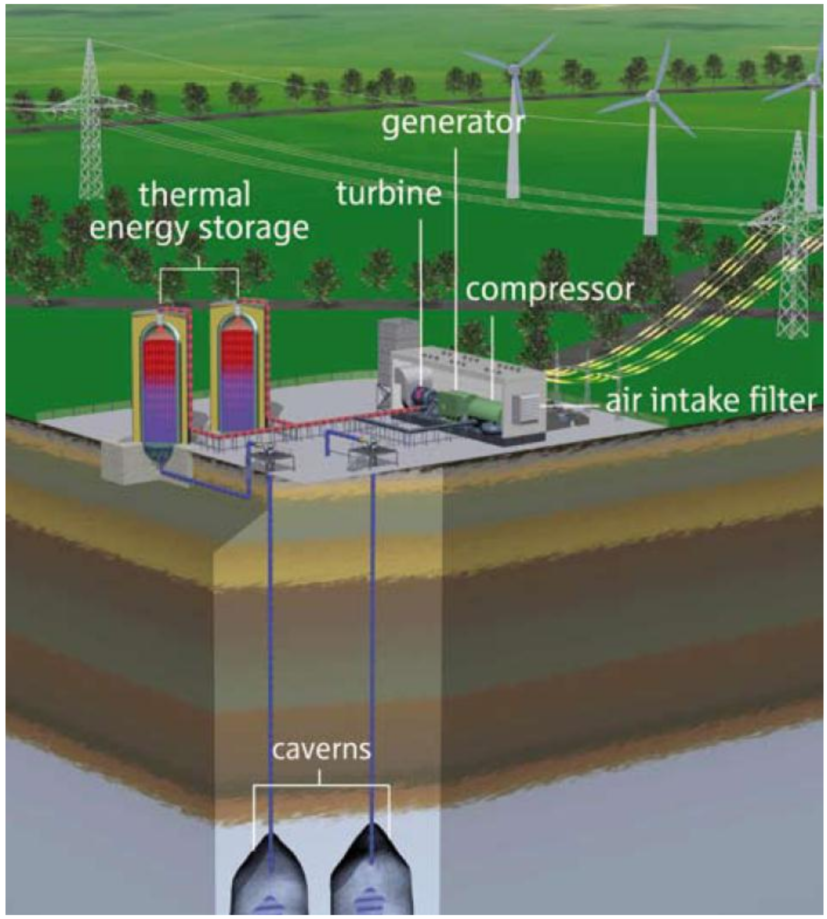

Figure 3.2.5 Adiabatic CAES having underground storage. Illustration from the ADELE project

Storage properties

The energy density of the storage is displayed in Figure 3.2.6 under assumption of reversible compression and expansion. The assumption means that in real CAES plants the energy density of the storage is about 60-80% of the values in the graph. It is seen that the adiabatic and diabatic CAES have the same energy density. However, for the diabatic system this production requires fuel input.

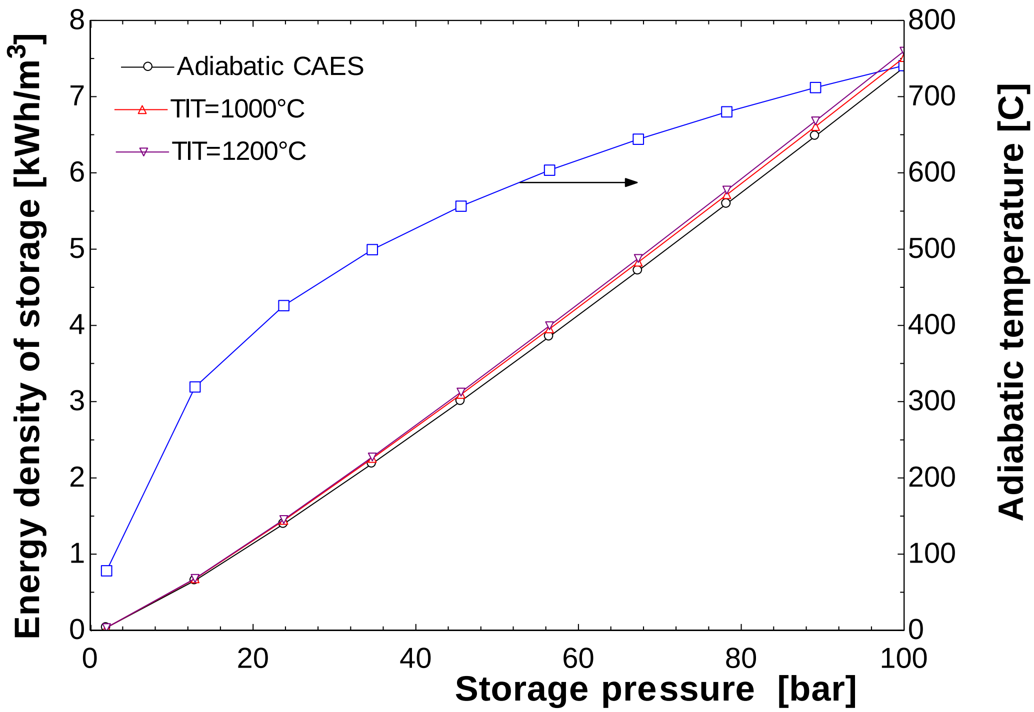

Figure 3.2.6 CAES energy storage density

The following is based on 1st and 2nd generatoin CAES, which is available on the market.

Available system sizes

Electrical power capacity 15 - 600 MW (second generation CAES)

The energy storage capacity is depending on storage volume (see “Storage properties”).

Connection to the grid

Like gas turbines

Energy loss and efficiency

No loss from the high pressure air storage (no leaks)

Degradation
No degeneration of the caverns is observed at the Huntorf plant nor at the Ll. Torup plant in Denmark, which is used for natural gas..

Experimental performance data
Only available for traditional CAES (Huntorf and McIntosh)

Expected life time
Cavern storage is widely used for natural gas storage and the degeneration depending on location can therefore be estimated (see also degeneration). The life time of the power train is similar to gas turbines.

Capital cost
Based on analysis on 2nd generation CAES by ESP (estimated prices)

Parameters	400 MW CAES2 with below ground storage	180 MW CAES2 with below ground storage	15 MW CAES2 with aboveground storage
Total Power, MW	420	180	15
Storage Hours	10	10	4
Estimated Specific Capital Costs, $/kW	850-900	850-900	1,200
Estimated Capital Costs, $/kWh	85-90	85-90	400-450

Maintenance (including prices)
The Mechanical part: Like gas turbines
Piping (incl. pipe based above ground storage): Like oil and gas installations
Caverns: See "Expected life time"

Potential CAES Suppliers
License / turnkey: Energy Storage and Power Corporation (ES&P)
Underground storage: KBB Underground Technologies DE
Air compressors: GE, MAN Turbo, Dresser-Rand, Ingersoll-Rand, Atlas Copco, Alstom
Expanders: GE, MAN Turbo, Skoda, Dresser-Rand, Ingersoll-Rand, Atlas Copco, Hitachi, Alstom
Recubertors: several suppliers

System delivery time
Two years: Typical dictated by the gas turbine delivery time, but also solution mining of the cavern is time consuming.

Guarantee
ES&P is giving performance garanties in some form.

Conclusions
Together with PHS CAES is expected to be the most cost effective storage technology for bulk storage of electrical energy. State of the art today is not handling the loss of energy due to the heating at the compression (charging the storage) and therefore natural gas (or other fuel) is needed for reheating when discharging the storage.

Even though start up times (for at least part of the capacity) is down to 3 minutes, the systems of today are not able to provide the fast regulation needed for xxx services.

This and the fact that the small 15 MW above ground system has not been demonstrated, CAES of today cannot be recommended for a small demonstration for providing short term power system services.

3.3 Flywheels

Working Principle
Flywheels store energy mechanically as kinetic energy by bringing a mass into rotation around an axis. According to classical, mechanical physics the kinetic energy of a rotating mass m in distance r from the point of rotation is $½·I·ω^2$, where I is the moment of inertia – equal to $m·r^2$ – and ω is the angular velocity (radians per second). It is seen from this expression that the kinetic energy of a rotating flywheel increases proportionally to the mass and to the distance from rotation point squared. The energy also increases proportionally to the angular velocity squared.
To maximize the stored energy for a given mass and rotation speed, the mass should be separated from the rotation point as much as possible. On the other hand the centrifugal force acting on the mass is $m·r·ω^2$ - and thus the requirements to the materials binding the mass to the rotation center - increases proportionally to the separation distance. This fact sets limits to the maximal available distance because of the properties (tensile strengths) of known, available construction materials. Whereas flywheels were formerly constructed of metallic materials, modern flywheels are often constructed – at least partially - by fiber composite materials. A simple, small laboratory flywheel constructed at Risoe with mechanical bearings is seen in Figure 3.3.1.

Figure 3.3.1. Small laboratory flywheel developed in the early nineties at Risoe and intended for mobile use in vehicles. The weight is 22 kg and the storage capacity at 36000 rpm is 4.6 MJ or 1.3 kWh. The power is in the range of 500 kW.

Storage properties
Flywheels can absorb and re-liberate electro-mechanical energy extremely fast. The response time is similar to the response times of batteries, meaning that flywheels react almost instantaneously on

demand (both ways). This property is attractive for ancillary services in the power grid and makes flywheels most suitable for frequency regulation. For a Beacon Power flywheel the company has estimated the ramp time in % of capacity per minute to be 1500. This means that the flywheel is on full capacity within 4 seconds.

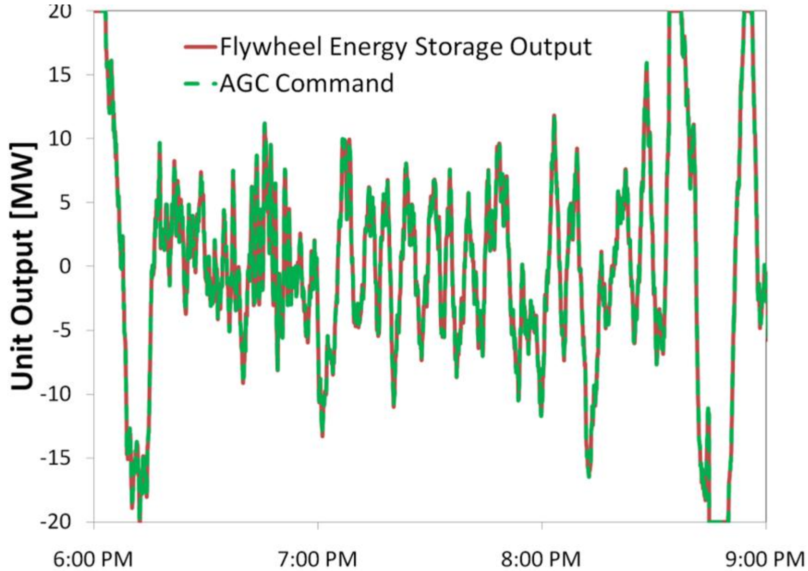

Figure 3.3.2 The figure shows the reaction of a flywheel (MW output) in response to signals from the Automatic Generation Control. It can be seen that within the accuracy of the graph (please note the axis scalings) the flywheel follows signals completely. Source: Beacon Power.

Modern flywheels are operated in high vacuum to eliminate (or reduce) drag. Likewise, the bearings are contact-less magnetic bearings, which means that the mechanical energy loses during a full storage cycle is ignorable from a practical perspective. However, power control and electronics do give rise to conversion loss so that the efficiency of a flywheel is in the range of 85 % if measured as energy into the <u>full system</u> divided by energy out of the system during the period of a complete, closed cycle.

The energy storage density – whether on volume or weight basis – is not impressive for flywheels as it is in the range of 1-2 orders of magnitude lower than for chemical methods for storing energy similar to the natural energy storage media oil and gas. This is, however, not very important for static applications.

Available system sizes

Flywheels for energy storage can be produced in numerous sizes ranging from multi MW utility applications to small systems intended for use in cars and buses. Beacon Power seems to be the most dominating producer of large scale flywheels. Their systems are based on a module flywheel size (a single flywheel) of 100 kW and 25 kWh the standard unit size is an assembly of 10 (or any multiple of 10) such modules summing up to 1 MW and 250 kWh. A photo showing the systems is given below.

Figure 3.3.3. Photo of Beacon Power flywheel installation in commercial operation in ISO New England, USA, since November 2008. The picture shows 10 flywheel modules lowered into the ground (5 on each side of the container). Source: Beacon Power.

Connection to the grid

Flywheel systems can be delivered either as turn-key installations (standard delivery) or in parts intended for customer´s own establishing of grid connection. For Danish industry the latter option may be of interest since Danish competences certainly exist and since it may open attractive future international market perspectives.

Beacon Power has suggested connection via radial tie or through a substation, as needed. The internal voltage is 480 V which is stepped up to 13.8 kV. The 13.8 kV is stepped up to the interconnection voltage as required, e.g. 60kV, 110 kV, 220 kV, 480 kV

High voltage transformer could be in supplier or customer scope.

Energy loss and efficiency

As mentioned above the flywheel technology in itself does not imply any significant energy loss even over prolonged periods. However, the power electronics taking care of converting primary power to the power format suitable for the flywheel and vice versa (the power electronics include rectifier, bus, inverter and converter) do give rise to loss of energy during the use of flywheels. This loss is naturally associated with charging and discharging the wheels and depends somewhat on the mode of operation. Beacon Power states that for a full charge/discharge cycle measured at the transformer terminals the energy loss is about 15%, whereas for typical operation providing frequency control the loss per cycle would be 6-7%.

Degradation

Due to its mechanical design and working principle flywheels have zero degradation in energy storage capacity over time. This is independent of how the system is operated and in particular independent og depth of charge and discharge, which is in noteworthy contrast to the properties of most electrochemical battery systems.

Experimental performance data

Historically flywheels for energy storage have been experimentally operated for decades. According to the reference given in [20] the world´s largest flywheel has been in operation since 1985. It consists of 6 discs each of diameter 6.6 m and thickness 0.4 m, weighing 107 t. The system can supply 160 MW over a 30 sec period and has shown excellent reliability, in particular concerning the mechanical construction. Another system developed by Okinawa Electric Company and Toshiba ROTES (rotary Energy Storage) [21] has been operated since 1996. The two examples indicate that flywheels represent highly reliable technology and this is supported also by more recent data where Beacon Power informs[22] that their system is capable of more than 150,000 charge/discharge cycles at constant full power.

Figure 3.3.4 is an excerpt from test data run in the New York ISO grid in the US.

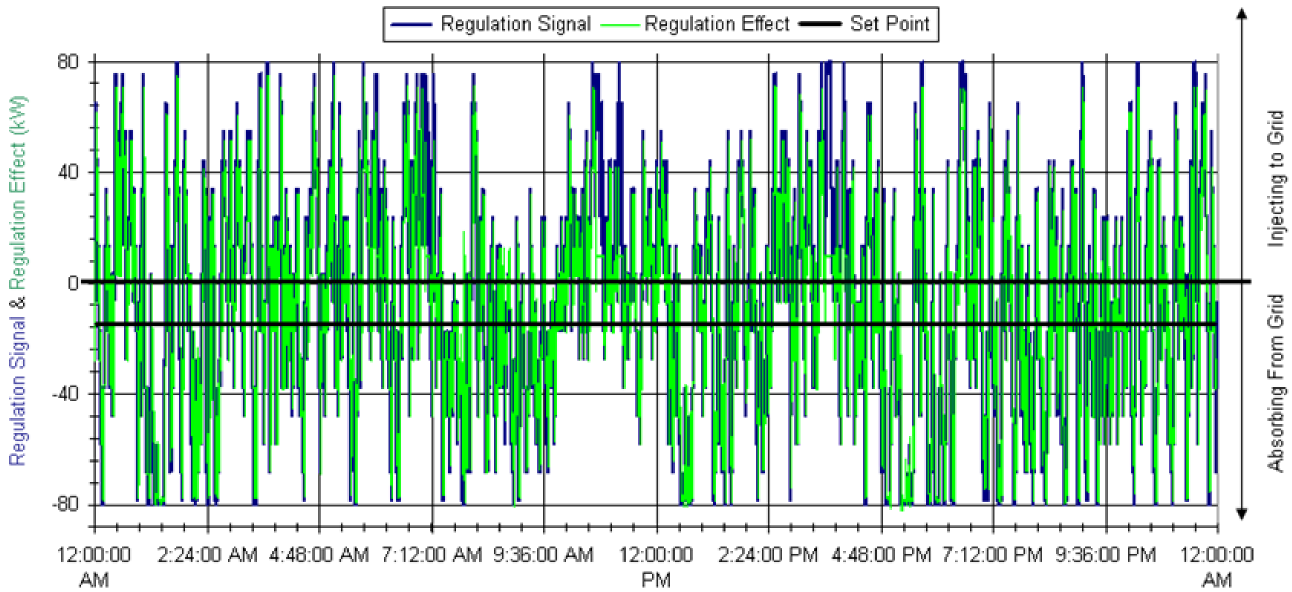

Figure 3.3.4. Test data run in the New York ISO grid in the US. The data shows regulation during one day and night after 8 months following fast changing frequency regulation signal. Availability to respond 97.2% of the time it was online. Source: Beacon Power.

Expected life time

The expected life time for a flywheel system is in the range of 20 years or 125,000 cycles

Capital cost

[20] Shin-ichi Inage, Prospects of Electricity Storage in Decarbonised Power Grids, IEA Working Paper Series, OECD/IEA, 2009

[21] http://www3.toshiba.co.jp/power/english/hydro/products/facts/rotes.htm

[22] http://www.beaconpower.com/files/Flywheel_FR-Fact-Sheet.pdf

System prices naturally depend on scope and size of purchase. The following information is provided by Beacon Power:

- Full system price would be in the range of ~$2.8 -3 million/MW without VAT to be adjusted for relative scope
- 2 flywheel (200 kW) system ~$1.6 million without VAT to be adjusted for relative scope

Maintenance (including prices)

- Detailed operating and maintenance manuals available
- No onsite operator presence
  - Remotely monitored
  - Specific faults shut down systems and notify operators
- Flywheels monthly visual inspections
- Monthly BOP maintenance (pumps/fans/chillers/etc.)
- ~4-5% of capital cost/year

Potential Flywheel Suppliers

A number of potential suppliers exist and are listed below. Most manufacturers seem to concentrate their product development towards niche applications like the market for uninterrupted power supply. We believe that the list below is close to exhaustive and a simple check of the web sites shows that some may not even really market flywheels in the sense that they have standard designs and products. However in relation to ancillary services particularly Beacon Power has pioneered a considerable development work and seems indeed to be a reliable supplier and collaboration partner and this is the reason why Beacon Power has been referenced frequently above.

Active Power, www.activepower.com
AFS Trinity Power, http://afstrinity.com/
Amber Kinetics, http://amberkinetics.com/
Beacon Power, www.beaconpower.com
Caterpillar Uninterruptible Power Supply, http://www.cat.com/power-generation/ups
Hitec Power Protection, http://www.hitecups.com/
Optimal Energy Systems, http://www.optimalenergysystems.com/
Pentadyne, http://www.pentadyne.com/
Piller GmbH, www.piller.com
Precise Power Corporation, http://www.precisepwr.com
Toshiba, http://www3.toshiba.co.jp/power/english/hydro/products/facts/rotes.htm
Vycon, www.vyconenergy.com
Urenco Power Technologies, http://www.urenco.com/

System delivery time

Delivery time for a flywheel system will depend somewhat on the local site schedule including permits from relevant Danish authorities. An optimistic schedule based on an order in beginning of 1st quarter of 2011 and site preparation beginning one quarter before flywheel delivery may be

- For purchase of 1-2 flywheels 4th quarter 2011 or first 2012
- For purchase of 1 MW module around 1st or 2nd quarter 2012

For purchase of 20 MW SEM initial operation 1st or 2nd quarter 2012 and full operation first half 2012

Guarantee

Guarantee and warranty will depend on supplier. At least the following can be obtained:

- System Performance guarantee
  - Power rating
  - Energy content
  - Response time
  - Grid requirements
- Parts and workmanship
  - One year or component supplier warranty whichever is greater

Conclusions

Technically flywheels certainly have a potential to provide fast reserves (up and down regulation) for ancillary services. Flywheels are indeed used for the purpose – more or less on a test basis – by North American ISOs. The major drawback of flywheels is the price, which is relatively high. However, payments for reserves are also relatively high in Denmark. A calculation of weighted average payments for Frequency-Controlled Normal Operation reserves (up and down) in DK2 over the period September 2009 – July 2010[23] yields € 46.47/MW per hr and a simple multiplication shows that this payment will be sufficient to pay for installation and interests over the expected depreciation period. The calculation may, however, be too simple since the market is not big. All together Energinet.dk buys FNR in the vicinity of 23 MW.

Flywheel characteristics for the benchmarking

start up time/ response time	Less than seconds when running
ramp time	25 % of power capacity per sec
cyclability (with reference to the needs shown in Fig. 2.1) and influence on lifetime	125.000. No loss of capacity
round cycle efficiency (electricity out over electricity)	85 %
power capacity	100 kW - modular
energy capacity	25 kWh in 100 kW unit
investment price per kW and kWh	2200 EUR/kW - 8800 EUR/kWh
operation and maintenance price	4-5 % of capital cost
expected lifetime	20 years

[23] http://www.energinet.dk

3.4. Pumped Hydro

Working Principle

Pumped Hydro Energy Storage (usually short PHS) is based on elevation and lowering of water and thereby changing its potential energy. The energy is exchanged with the power system via use of electricity during pumping the water from lower to higher levels and vice versa when the water is driving electric generators flowing back to the low level. The energy storage capacity of PHS therefore depends on the amount of the pumped water (essentially reservoir size) and the vertical distance between the two levels as described by the equation:

$$E = M \cdot g \cdot h = F \cdot h$$

Where E is the storage capacity (Wh), M the amount (mass) of pumped water, g is the gravitational constant, h the vertical distance between the two levels and F is the gravitational force acting on the water.

Traditionally (because of the importance of h in the above equation) PHS has almost exclusively been of interest in countries possessing mountain areas where natural, geographical conditions encourage use of the technology due to directly available height difference. However new concepts, which do not to the same extent depend on geographical conditions, have been proposed but still need considerable development to become technically and economically feasible. One examples of such new ideas are shown in Figure 3.4.1, where underground water reservoirs are utilized (the idea has been proposed many, e.g. in [24] and [25]. Another example of new ideas/concepts has been proposed by a Dutch/Danish group and called an "Energy Island". Figure 3.4.2 shows the idea, which is based on digging out a deep pond at sea location and pumping water in and out.

Pumped Hydro Storage is based on well-known and long proven technologies, namely water turbines – as used in hydropower plants – and heavy duty water pumps usually combined in one reversible pump-turbine.

[24] http://cleantechnica.com/2009/09/02/pump-hydro-underground-to-store-wind-power/
[25] G. Martin and F. Barnes, Aquifer Underground Pumped Hydro, CERI Research Report, June 30, 2007, University of Colorado

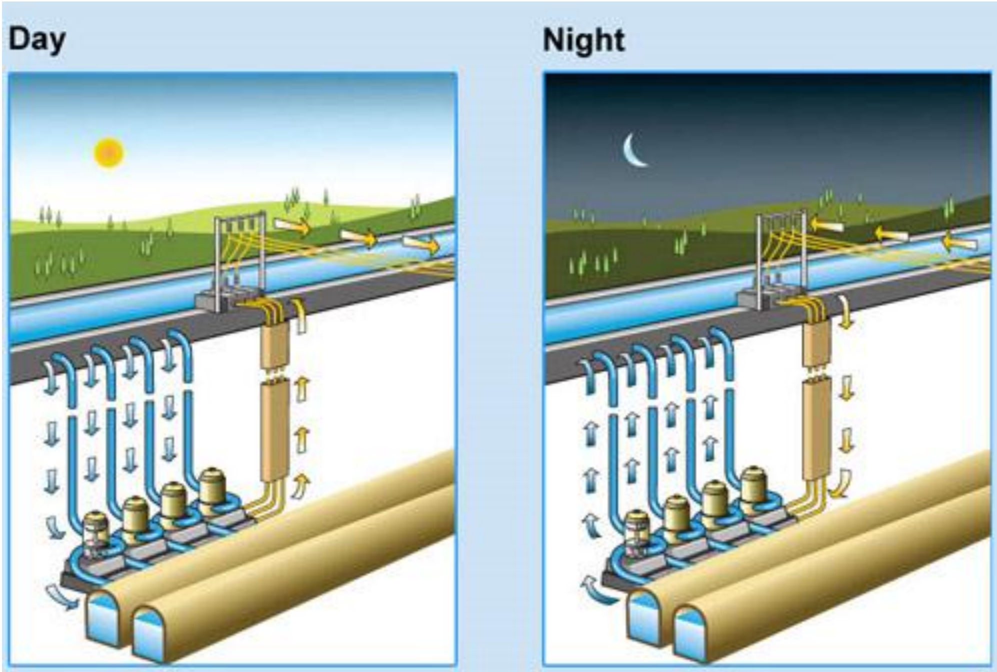

Figure 3.4.1. Schematic illustration of PHS based on underground water reservoirs. The figure shows the two principal modes of operation.

b

Figure 3.4.2. Artistic drawing of an Energy Island[26]. Water from the deep interior of the island is pumped out in periods of surplus electricity. The electricity can subsequently be regenerated when water is allowed to flow back via turbines. The concept may be expanded with wind turbines (on-shore foundations), solar cells (circle in the middle) as well as algae production.

[26] Gottlieb Paludan Architects

Storage properties

Pumped Hydro Storage installations are able to extract and reject electrical energy to/from the power grid relatively fast although not as fast as capacitors, flywheels and batteries. For the Dinorwig installation, which has been in operation since 1984, the time from standby to 1320 MW (installed capacity is 1800 MW) is informed by First Hydro Company to be 12 seconds[27]. On the other hand, this is called the fastest "response time" of any pumped storage plant in the world[28].

Pumped storage technology can provide a variety of ancillary services including network frequency and voltage regulation, reserve capacity (spinning and non-spinning reserves), black start capabilities, as well as reactive power production. Provision of such services is done by many existing PHS plants an example being the Vattenfall Goldisthal installation in Germany[29].

Available system sizes

PHS systems are designed specifically in accordance with external conditions and requirements and thus no standard or module size exists.

Connection to the grid

Energy loss and efficiency

Round cycle efficiencies for PHS plants are in the range of 70 – 75 %[25]. Figure 3.4.3. below shows the distribution of losses in a hydropower plant. The maximum obtainable efficiency is approx. 90 %. Since the operation cannot always be kept at maximum the realizable efficiency is rather around 87-88 %. If this number is squared (assuming similar loss structure during pumping) to take the pumping a turnaround efficiency

[27] http://www.fhc.co.uk/dinorwig.htm
[28] http://www.darvill.clara.net/altenerg/pumped.htm
[29] http://www.hydroworld.com/index/display/article-display/351208/articles/hydro-review-worldwide/volume-15/issue-1/articles/goldisthal-pumped-storage-plant-more-than-power-production.html

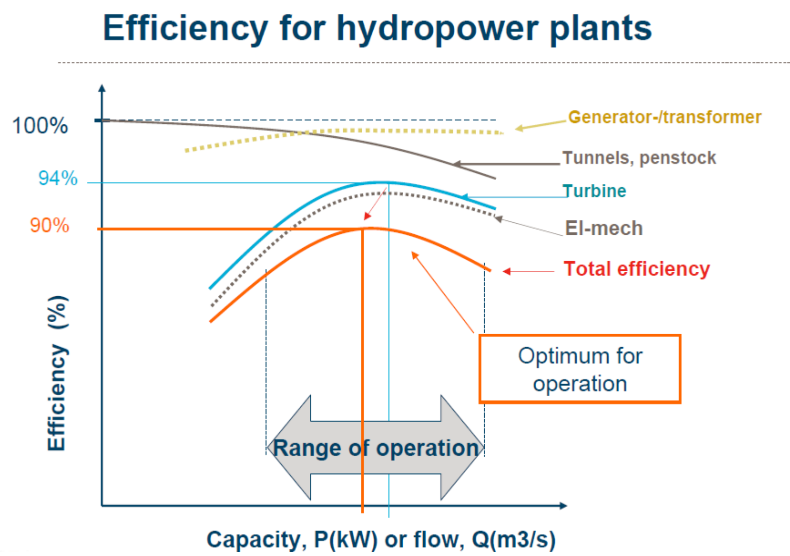

Figure 3.4.3. Efficiency of hydropower plants and break down of losses [30]

Degradation

Degradation is not inherent in pumped hydro storage technology except for normal wear of mechanical and electrical parts in the plant.

Experimental performance data

Using Vattenfall´s 1,060 MW Goldisthal pumped-storage plant[31] as an example this plant has provided ancillary services since being commissioned in 2004.Because of the large capacity of the units, a large regulation range has been available. This is used daily for the grid frequency control. The asynchronous machines can be regulated from 40 MW up to 265 MW, while the synchronous machines can only be regulated from 100 MW to 265 MW. Thus, the asynchronous machines provide 60 MW more for regulation. This allows Vattenfall to take advantage of the lower basic power output of 40 MW, saving water to be used for later generation.

Expected life time

The first pumped hydro energy storage plant was installed in Dresden in 1929 [32] and is still in operation. Characteristically demonstrated life times of PHS plants are over many decades.

[30] Jon Ulrik Haaheim, “Operational Issues”. Presented at Hydrovision 2008, Hydropower Sustainabilty Assessment Forum, Sacramento 2008.

[31] http://www.hydroworld.com/index/display/article-display/351208/articles/hydro-review-worldwide/volume-15/issue-1/articles/goldisthal-pumped-storage-plant-more-than-power-production.html

[32] http://www.cigre-a1.org/Site/Events/download/13%20-ANDRITZ%20Giga-Watt%20Generation%20Panel%20SessionID31VER40.pdf

Capital cost

Capital costs for PHS differ very much. Reliable, experimentally confirmed numbers are only available for traditional geographically determined installations and reported to be in the range of 800-1000 EUR/kW and 80-100 EUR/kWh (see table below).

Potential PHS Suppliers

Alstom, www.power.alstom.com/hydro
Andritz, http://www.andritz.com

Conclusions

Pumped hydro storage is suitable for use in ancillary service and is already used for this purpose by utility companies all over the world e.g. Vattenfall in Germany[33]. Pumped hydro is also well suited for storage of energy over somewhat longer periods (bulk storage) than is the object of the present survey. For geographical reasons Denmark is not a priori suited for traditional pumped hydro power installations. However, new concepts for pumped hydro storage are being studied or developed and may prove to be appropriate for Danish conditions. Such new installations may profit from taking part in both the market for bulk long-term energy storage and the market for ancillary services, but within the scope of the present project ideas (i.e. experimental testing and demonstration) we find that PHS is not suitable.

Pumped Hydro Storage characteristics for the benchmarking

start up time/ response time	Seconds
ramp time	4 % of power capacity per sec (50% in 12 sec)
cyclability (with reference to the needs shown in Fig. 2.1) and influence on lifetime	Capacity does not depend on cycling
round cycle efficiency (electricity out over electricity in)	75-85 %
power capacity	Multi MW
energy capacity	Depends on size of reservoir
investment price per kW and kWh	800-1000 EUR/kW and 80-100 EUR/kWh[34]
operation and maintenance price	Few % of capital cost
expected lifetime	At least decades

[33] http://www.hydroworld.com/index/display/article-display/351208/articles/hydro-review-worldwide/volume-15/issue-1/articles/goldisthal-pumped-storage-plant-more-than-power-production.html
[34] http://electricity.ehclients.com/images/uploads/capital.gif

3.5. Super Capacitors

Working Principle
Supercapacitors are devices able to store electrical energy by separating charges (charge carriers) similarly to what takes place in a conventional capacitor. Supercapacitors are called different names and “Electric (or Electrochemical) Double Layer Capacitors” (EDLC) as well as “ultracapacitors” are frequently found synonyms.

Figure 3.5.1. gives a schematic presentation of the construction and working principle of supercapacitors and shows why they are also called electric double layer capacitors.

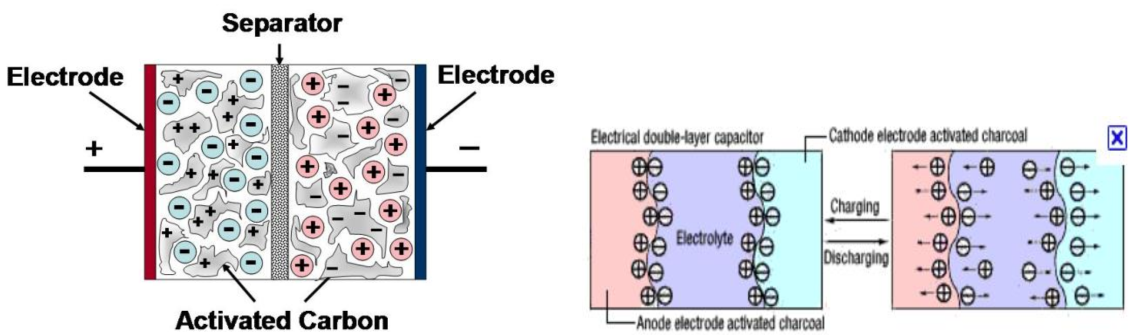

***Figure 3.5.1**. The **left** part[35] shows the construction of a supercapacitor. The shown electrodes consist of finely structured (nanostructured) carbon which gives a large electrode surface area and accordingly a large double layer as well as short diffusion distances for the migrating charged particles. The **right** part[36] of the figure illustrates the mechanisms of charging and discharging. At charging the charged particles are attracted to the electrode surfaces and thereby form the double layer. During discharge the particles mix randomly.*

When an electrical charge dq is moved a in an electric field the required energy dU is

$$dU = V \cdot dq$$

where V is the potential (voltage) difference between the starting and end points of the movement. Thus, if a capacitor is charged to the voltage V the energy stored is equal to

$$U = \int_0^Q \frac{q}{C} \cdot dq = ½\, C \cdot V^2$$

where the capacitance C is defined as Q/V and is a characteristic property of the capacitor.

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35 http://www.enerize.com/superCap.php
36 http://www.elna.co.jp/en/capacitor/double_layer/principle/

Storage properties

The capacitance of supercapacitors is usually several orders (3-4) of magnitude larger than for traditional capacitors but the available range of working voltage is usually lower. One of the largest capacities reported for a supercapacitor is a 5000 F (NESSCAP[37]). Data sheets[38] from one of the leading manufacturers of supercapacitors (Maxwell Technologies) shows the following characteristics for supercaps: Wh/kg: up to 5-6 and W/kg: up to 27,000. These numbers express a central strength and weakness of supercaps, namely the low energy density and the (extremely) high power density. For immediate comparison the corresponding numbers for modern Li-ion batteries are over 100 Wh/kg and a few thousand W/kg[39].

Similar to other capacitors, the voltage varies with the energy stored (see equations above).

Available system sizes

Supercaps are mainly produced as units for markets and applications, which do not require energy or power capacity in the range considered in the present study. The largest standard units produced by leading manufacturers today are in the range up to a few hundred Wh. On the other hand Meiden Company[40] has manufactured a 10 MW for compensation of fast voltage changes in power systems

Connection to the grid

If used for energy storage (large systems) effective storage and recovery of energy from supercaps requires quite complex electronic control and switching equipment. This inevitably leads to corresponding losses of energy.

Energy loss and efficiency

The efficiency of supercaps depend somewhat on how the capacitor is used, the losses being associated with internal resistance of the device. Efficiency down to 85 % is reported but more often 90-95 % are reported by independent authors[41].

Degradation

Degradation does not appear to be problematic for supercaps. Their energy storage and power delivery mechanisms involve no chemical reaction, and therefore they can be charged and discharged hundreds of thousands to millions of times with minimal performance degradation[42].

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37 http://www.nesscap.com/products_lineup.htm
38 http://www.maxwell.com/pdf/uc/Maxwell_UC_comparison.pdf
39 http://www.a123systems.com/cms/product/pdf/1/_ANR26650M1A.pdf
40 Shin-ichi Inage, Prospects of Electricity Storage in Decarbonised Power Grids, IEA Working Paper Series, OECD/IEA, 2009
41 A.F.Burke, Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles, Proceedings of the IEEE | Vol. 95,No. 4, 806, April 2007
42 http://www1.eere.energy.gov/vehiclesandfuels/pdfs/success/ultracapacitors_5_01.pdf

Expected life time

Supercapacitors are considered to be durable and long-term working devices with 15-20 years lifetime.

Capital cost

The cost reduction for supercapacitors has been impressive over the past 10 years. Costs have decreased from $0.6-$2.5/F in 1997 to $0.3-$0.7 /F in 2002 to less than 10 cents/F today.[43]

Maintenance (including prices)

Supercaps are generally viewed as near-zero maintenance components and for that matter have perfect characteristics for a grid system. In some designs exposure to overvoltage may induce production of gases by consumption of water from the electrolyte. In this case water has to be refilled.

Potential Supercapacity Suppliers

Numerous suppliers/manufacturers are active on the supercap market examples being:

Maxwell Technologies, http://www.maxwell.com/
NESSCAP, http://www.nesscap.com/
MEIDEN, http://vacuum-capacitors.meidensha.co.jp/en/index.html
ELNA-AMERICA, http://www.elna-america.com/

System delivery time

For small, standard units delivery is off shelf and immediate.

Conclusions

In an analysis NanoMarkets[44] predicts a $1.8 billion frequency regulation market for supercaps with 60 percent of this frequency regulation market coming from microgrids. The conclusions go on “Add in somewhat over $200 million for other applications and the Smart Grid supercapacitor market will reach a very healthy $3.8 billion in 2015”.

Probably supercaps are still relatively far from widespread utilization as stand-alone components in grid ancillary service. However, supercaps may have an important role to play in conjunction with batteries in the sense that supercaps are more capable to deliver (or receive) large power than are batteries. Therefore - if paired – supercaps might take care of large, power spikes which are unhealthy for batteries, whereas the battery might take care of the long-lasting loads, which supercaps would be unable to tackle due to limited capacity.

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[43] http://nanomarkets.net/articles/article/supercap/P2/
[44] http://nanomarkets.net/articles/article/supercap/P3/

Supercap characteristics for the benchmarking

start up time/ response time	Much less than sec
ramp time	Up to 100 % of power capacity per sec
cyclability (with reference to the needs shown in Fig. 2.1) and influence on lifetime	Millions of cycles without losing performance[45]
round cycle efficiency (electricity out over electricity in)	High – up to 95%
power capacity	Up to 100 kW unit available (modular)
energy capacity	300 kWh in unit
investment price per kW and kWh	250 EUR/kW and 6000 EUR/kWh[46]
operation and maintenance price	Ignorable
expected lifetime	years

[45] http://www.squidoo.com/supercapacitors
[46] http://electricity.ehclients.com/images/uploads/capital.gif

3.6. Other Technologies

Many techniques and ideas for storing electricity have been proposed over time, some of which appear to be somewhat discursive and are not discussed here. However, two techniques hold realistic promises and are therefore included in the present section: hydrogen storage and superconducting magnetic energy storage, SMES.

Working Principle of Hydrogen Storage
Electricity can be readily converted to hydrogen by water electrolysis, where the water molecule is split into its constituents hydrogen and oxygen. Hydrogen can then be stored and re-electrified either by direct combustion, e.g. in a turbine, or electrochemically in a fuel cell.

Storage properties
Hydrogen is the lightest of all elements and a gas at atmospheric pressure and room temperature. The volumetric energy density of hydrogen gas at 1 bar and 300 K is low and therefore hydrogen is not immediately suitable for storage in this form. At room temperature pure hydrogen is consequently stored at high pressure. Historically, 2-300 bar has been used, but new composite materials allow operation of pressurized hydrogen up to 7-800 bar, where the energy density is approx. 12 MJ/l (as compared to approx 33 MJ/l for the well-known gasoline). Hydrogen can also be stored in cryo-containers at low temperature (approx 20 K) in liquid state and finally hydrogen can be stored indirectly in chemical compounds like hydrides or similar, which are often solid, but may also be gaseous or liquid. However, although many storage options are available, they are all inefficient because of energy loss during conversion processes and/or complicated to use. For these reasons hydrogen has not yet found widespread use as an energy vector and it is still uncertain which role hydrogen will have in the future energy system.

Energy loss and efficiency
The electric efficiency of modern electrolyzers is about 70%. If this is combined with 50% efficiency of a fuel cell, the overall efficiency is about 35% and this number does not take possible losses during storage into account. The low efficiency must be considered a severe weakness of hydrogen as an energy vector in general.

Degradation
The various conversion steps involved in using hydrogen as a storage medium for electricity are accompanied with degradation processes, but a long term stability for fuel cells (power density vs. current density) showing degradation of 0.6% over 1000h [47] does not appear to be a serious problem.

Experimental performance data
Using hydrogen for storage implies two opposite chemical reactions: dissociation of water and combination of hydrogen and oxygen. These steps are usually performed in two different equipments

[47] A.S.Pedersen, Private internal Risoe communication

each optimized for the respective reaction. Both electrolyzers and fuel cells have been operated for decades and the long time performance has been demonstrated. Both are sold on commercial terms for a number of applications one good example being fuel cells for power backup for telecommunication, which is marketed by e.g. the Danish company Dantherm Power[48].

Capital cost

According to the US Department of Energy, DoE, the most widely deployed fuel cells cost about $4,500 per kilowatt[49]. For comparison (data from the same source), a diesel generator costs $800 to $1,500 per kilowatt, and a natural gas turbine can be $400 per kilowatt or even less.

Potential Suppliers of Fuel cells and Electrolyzer

Hydrogenics, http://www.hydrogenics.com/
Ballard, http://www.ballard.com/
IRD Fuel Cell Technology, http://www.ird.dk/
Topsoe Fuel Cell, http://www.topsoefuelcell.com/

Conclusions

Extensive, international activities focused on development of efficient and cheap fuel cells have been going on for decades and within the latest years also electrolysis has become the subject of a steep increase in interest and funding. Nevertheless it is the opinion of the project participants that fuel cells/electrolysis still have a way to go before a commercial potential can be released and the technical performance is compatible. For electricity storage aiming at fast reserves for ancillary service the round trip efficiency is deemed to be too low. Too much useful energy is lost as heat in the various conversion processes and furthermore hydrogen technologies are unlikely to meet the requirements concerning response time (see also below). For these reasons hydrogen is ruled out for the present purpose.

Hydrogen characteristics for the benchmarking

start up time/ response time	Seconds if device is warm and running
ramp time	50 % of power capacity per sec
cyclability (with reference to the needs shown in Fig. 2.1) and influence on lifetime	No of cycles to 80% capacity: thousands
round cycle efficiency (electricity out over electricity in)	35 %
power capacity	Modular
energy capacity	Modular
investment price per kW and kWh	3500 EUR/kW (FC) and 230 EUR/kW (EC)[50]
operation and maintenance price	1-2 % of capital cost[48]
expected lifetime	5-10 years depending on use

48 http://www.dantherm-power.com/Products/Backup_power.aspx
49 http://www.fossil.energy.gov/programs/powersystems/fuelcells/
50 Technology Data for Energy Plants, Danish Energy Agency, June 2010

Working principle for SMES

In an SMES electric energy is stored in a magnetic field created by circulating current in coils made from superconducting materials and kept at superconducting temperature. For a true superconductor there are no resistive losses during the storage process.

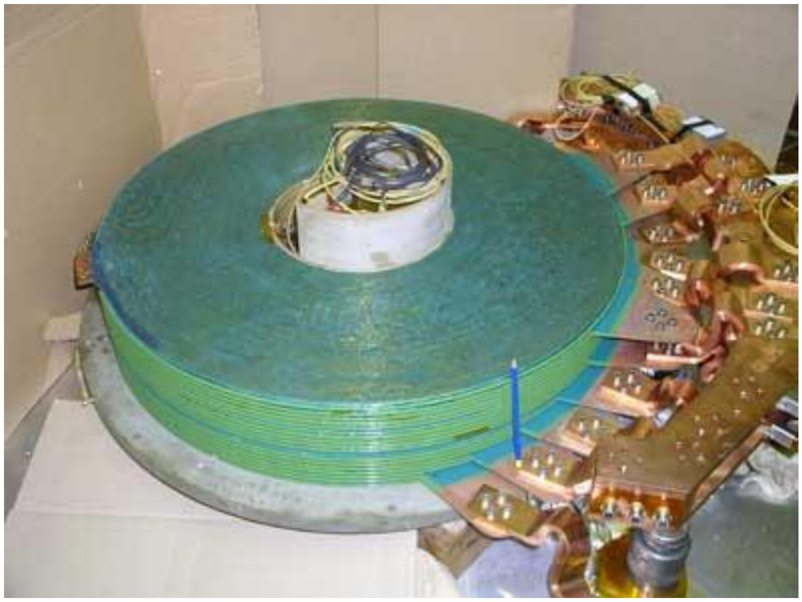

Figure 3.6.1. Photo of a laboratory scale SMES at the NEEL, CNRS, France[51]. The device is based on BiSrCaCuO and is able to store approx 800 kJ (about 0.2 kWh). Coil dimensions are: external diameter 814 mm and height 222 mm.

Storage Properties

Since no energy conversion is involved in the storage process of an SMES the efficiency of charging and discharging is very high. Like for other electricity storage techniques, losses are associated with power electronics and conversion.

Capital Cost

A study made at Sandia Nat. Lab. In 1997[52] the cost of a 30 MW/375 kWh SMES at Anchorage Municipal Light and Power is assessed to be 1475 USD/kW and 117360 USD/kWh (1995 prices). The numbers should probably be used cautiously.

Conclusions

SMES still need considerable development before it can be taken into immediate commercial consideration for use in ancillary service. Although performance data for SMES do seem to exist (as

[51] http://neel.cnrs.fr/spip?article794

[52] A. Akhil, S.Swaminathan and R.K. Sen, SANDIA REPORT, SAND97-0443, UC-1350, Printed February 1997

an example see [53]) they are not technically reported convincing way. The authors of this report have not been able to find commercial manufacturers of SMES.

SMES characteristics for the benchmarking

start up time/ response time	Instant
ramp time	Very high
cyclability (with reference to the needs shown in Fig. 2.1) and influence on lifetime	No of cycles to 80% capacity: not known
round cycle efficiency (electricity out over electricity in)	Close to 100 % excluding power conversion
power capacity	Variable
energy capacity	Variable
investment price per kW and kWh	1134 EUR/kW and 90 kEUR/kWh (uncertain)
operation and maintenance price	Not known
expected lifetime	Reliable data not available

53

http://webcache.googleusercontent.com/search?q=cache:7fmFxcXR6s4J:www.chuden.co.jp/english/corporate/press2007/0615_1.html+chubu+electric+smes&cd=5&hl=en&ct=clnk&gl=dk

3.7. Power Conversion – Power electronics and grid-interfacing

This section is subdivided into the following topics:

- Power and Voltage scope
- Description of some possible power converter topologies
- Description of power converter capabilities (response time, frequency control, reactive power control, voltage support, black-start etc)
- Estimation on costs (depending on capabilities)
- Description of technology interface. Identification of opportunities and limitations for power conversion to/from each of the storage technologies (WP2-7)

Power and Voltage scope

In the Danish system the required power level for an electrical energy storage targeting fast grid support services is expected to be limited to around 20 MW in total. Thus, a scenario for storage units could be 1-2 MW units spread around in the system. For this unit power level, the most suitable power converter voltage level using standard technology is a low voltage rating of 3x400V or 3x690V. If bigger units are chosen, higher voltage levels might be relevant, see below.

Description of some possible power converter topologies

There are basically 3 different voltage classes :

Low Voltage (LV) = 400-690 V
Medium Voltage (MV) = 1-35 kV
High Voltage (HV) > 35 kV

High Voltage Converters only exist for HVDC and a few derived special applications (High Voltage Motor Drives for offshore applications) in the power range from 50 MW and upwards, so HV Converters are not a realistic choice for Power Converters for 1-2 MW Storage Applications.

Medium Voltage Converters (1-35 kV) have been intensively discussed for wind turbine applications. This topic is discussed in details in the nice presentation from 'The Switch' [54]. Furthermore, for wind turbine applications, it seems, that most (if not all) new designs are based on Voltage Stiff Inverters (VSI) due to the strict demands on control performance (on both generator and grid side) and grid harmonics. For a modern storage device it seems reasonable to demand similar control and grid harmonic performance, i.e. to select a VSI topology. In wind turbine applications one of the fundamental ideas (or goals) with MV converters is to get rid of the on-board 50 (or 60) Hz transformer. This gives a rather high demand on the converter voltage rating, as standard voltages for modern wind farm cable grids are 33 kV. Such a converter is not yet on the market.

[54] A comparison of low voltage and medium voltage wind turbine drive trains, EWEC 2010, April 22, Warsaw, Anders Troedson, The Switch

Low voltage and medium voltage converters

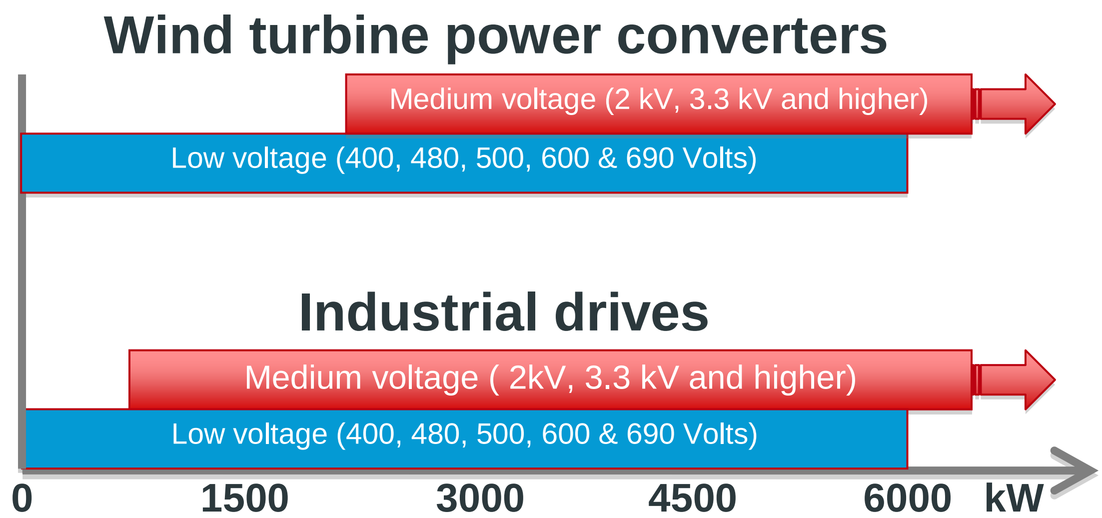

Figure 3.7.1. Typical Power range for Low Voltage (LV) and Medium Voltage (MV) converters for Wind Turbine and Industrial Drive applications. Data from [48)] above.

The difference in minimum power levels for Medium Voltage (MV) drives between wind turbine and industrial drive applications can be explained by the short cable lengths (generator-converter-transformer) in wind turbines, which make Low Voltage converters competitive up to 5-6 MW here. In some industrial drive applications, the cable lengths are hundreds of meters, which will make a MV solution more competitive.

Low Voltage converters will be well suited for energy storage units (up to 5-6 MW) based on flywheels, batteries or other storage elements with a limited physical size (or more specific limited cable lengths). This is due to the fact that the grid transformer can be placed close to the converter and the storage unit, so it is reasonable to select a converter topology similar to the wind turbine converter shown below. Depending on application demands and the power level, the converter can be split in more parallel units in order to make redundant operation possible.

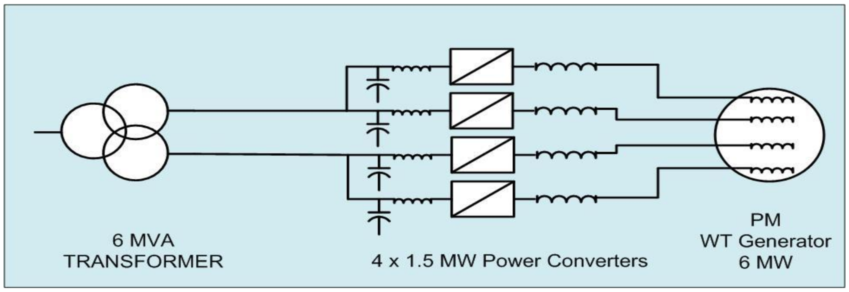

Figure 3.7.2. Low Voltage converter setup for 6 MW wind turbine. Data from [48)] above.

Low Voltage converter topology, efficiency and performance.

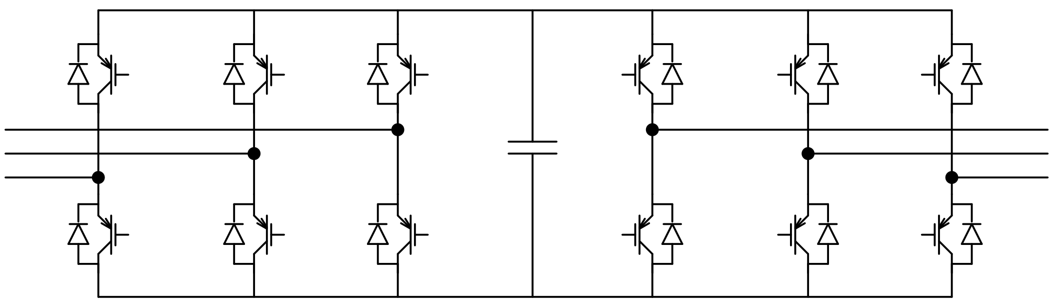

Figure 3.7.3. Topology for standard 2-level Voltage Stiff Inverter (VSI) back-to-back (B2B) converter (AC-DC-AC).

The efficiency for a back-to-back (B2B) converter (AC-DC-AC) is around 96-97%, so for DC-AC converters (single inverter stage) the efficiency will be around 98-98.5%.
For topologies with DC-DC + DC-AC (DC-DC-AC) conversion the efficiency should be similar to the AC-DC-AC (B2B) converter. The DC-DC converter is quite similar to the AC-DC inverter shown above, just with one or two inverter legs instead of three.
For DC-storage units with a limited voltage variation during operation (like some batteries) it would be beneficial from a cost as well as efficiency point of view to use only the DC-AC conversion stage (DC-AC inverter).

Description of power converter capabilities (response time, frequency control, reactive power control, voltage support, black-start etc)

The converter shown above is built from 2 DC-AC inverters put back-to-back. The inverters can only handle step-down conversion, i.e. the AC voltage (peak-peak) on both sides always has to be smaller than the DC-link voltage. The AC voltage (and frequency) can be controlled continuously down to zero. The upper AC voltage constraint combined with the standard (IGBT) voltage levels gives following practical voltage limits for 690V and 400V converters, respectively:

Uac(max) = Udc(max)/sqrt(2) = 1100V/sqrt(2) = 778 V for 1700 V IGBT based converters

Uac(max) = Udc(max)/sqrt(2) = 800V/sqrt(2) = 565 V for 1200 V IGBT based converters

It should be noted, that the standard IGBT voltage levels used only allows 13% (778/690) voltage headroom for a 690 V converter versus 41% (565/400) for a 400 V converter. This 'hidden' voltage reserve might be useable for PQ-control, see below, or other high voltage situations, in order to avoid otherwise necessary overrating (decrease rated operating voltage and increase current to keep VA rating).

Below is shown a PQ-diagram example for a wind turbine converter. This illustrates the impact of the voltage limitation on the possible PQ-generation towards the grid (without the voltage limitation it would simply be symmetrical semi-circles like the blue curve). These limitations can be avoided by increasing the DC-voltage (might be possible in a 400 V converter) or by reducing the transformer voltage at the cost of a higher power/current rating on the converter (might be necessary on a 690 V converter).

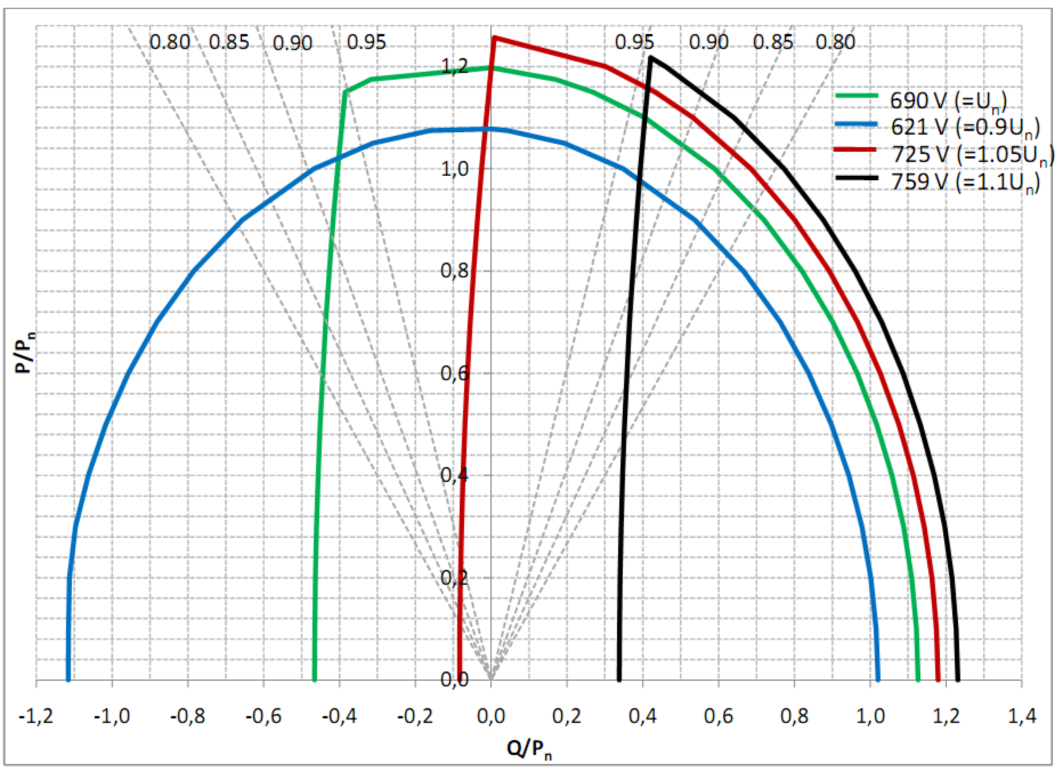

Figure 3.7.4. PQ-diagram example for a wind turbine converter

The overload capability for the power converters discussed here is limited, both in current/power and time. Typical specifications could be a 1 second at 200% current or a 60 second at 150% current limit. These limitations are often implemented with (thermal) protection functions in the converter control, which limits how often an overload can be applied.

The Control performance will normally not be a limiting factor here. It is typically based on cascade control with fast inner current control loops (20 to 200 Hz bandwidth). Since power and reactive power are directly controlled by the current in voltage stiff systems, the power control can be made very fast, in the order of 1-10 ms rise time for a 100% power/current step!!

In this way, grid support functions like frequency control, reactive power control and voltage support can be provided very fast and controllable, just limited by the PQ-limitations mentioned above. Black start support is also possible, since the converter is a controllable voltage source, but of course limited by the PQ-limits and overload capability.

The DC-link capacitor has typically a very small energy storage capacity, equivalent to a few milliseconds of full power, so there is no useable extra energy storage here.

The short circuit power (or impedance) contribution from a current controlled converter as described above depends on the characteristics and functionality of the software-based control, and it is therefore not possible to define a simple equivalent circuit, that will describe the general behavior of any power converter towards non-ideal voltage wave-forms on the grid. In a given situation, the control system can be designed to give priority to either voltage quality (reactive power, harmonic power/current, unbalance compensation etc.) or active power transfer (or a compromise) when using its power handling capability. Due to the active control the impedance towards certain harmonics might be vary from zero to infinite, as an example, but with restrictions on the possible current levels within the converters capacity (or a reserved fraction hereof)

Startup time

The startup time depends very much on the initial conditions, and can vary from milliseconds to hours. Below are listed a number of possibilities (considering only the converter, not other possible storage/balance of plant limitations):

Active standby (converter running grid connected at no-load) – 0 ms
Hot standby (converter coasted, control active, grid contactor closed/open) - 10/500 ms
Warm standby (converter preheated, control system to be started) - 1 minute
Cold start (converter to be started/preheated etc.) – 1 to 30 minutes (depends on preheating/ambient conditions)

In a storage applications, it would be possible to always keep the converter ready for operation. With a proper control strategy (including control of ambient conditions), a very short start up time is possible (down to the reaction time of a contactor !).

If the storage unit requires continuous grid support (energy), the converter might have to be grid connected continuously. This will eliminate the start up time (for the converter) at the cost of some no load/low load loss for the converter switching, pumps, fans and control electronics supply.

Estimation on costs (depending on capabilities)

It is difficult to give exact numbers on operating and initial cost of a converter, unless all specifications are at hand. This includes, of course, issues like ambient conditions, cooling and ventilation system, standby operation requirements and so on. Anyway, a rough guess on a Low Voltage Converter (690 or 400 V) could be 75-150 EUR/kW for a 0.5 to 1 MW converter.

Description of technology interface. Identification of opportunities and limitations for power conversion to/from each of the storage technologies (WP2-7)

Most of the described storage technologies will require power electronic converters as part of the grid interface, namely batteries, flywheels, super-capacitors, Fuel-cells and SMES. All of these, except perhaps some battery types, will require 2-stage conversion power converters due to (vide range) variable voltage levels.

The remaining storage technologies, pumped hydro and CAES, might also benefit from power converters for variable speed operation, because it will allow part load operation with good efficiency.

The power electronic converter are today used in a number of grid support functions (Static VAR Compensators – STATCOM, Dynamic Voltage Restoring etc.). In such cases, it is possible to include storage capacity to the converter, if so desired, see e.g. ABB SVC with storage.

A competing technology to energy storage might actually be power converter based variable speed generators, because the drive machines (turbine, diesel/gas engine etc.) can be operated at an (much) extended power range at high efficiency.

Potential suppliers of Power Converters for storage units
ABB – has an impressive program covering Low Voltage, Medium Voltage and High Voltage,
See a.o.:
http://www.abb.com/product/us/9AAC167805.aspx?country=DK

Siemens, Converteam, Alstom, Danfoss, Vacon, American Superconductor, The Switch and many other suppliers of industrial drives are also potential suppliers of converters for storage applications.

Power Converter characteristics for the benchmarking

start up time/ response time	milliseconds seconds when running
ramp time	> 100 % of power capacity per sec
cyclability (with reference to the needs shown in Fig. 2.1) and influence on lifetime	> 1000.000. No loss of capacity, low impact on lifetime
round cycle efficiency (electricity out over electricity) - converter efficiency only	92-94 % for AC/DC/AC (2 stage) 96-97% for DC/AC (1 stage)
power capacity Low Voltage converter	0-10 MW – modular above 0,5 to 1 MW units
energy capacity	Determined by energy storage
investment price per kW	75-150 EUR/kW
operation and maintenance price	< 1 % of capital cost (part of BOP service)
expected lifetime (scheduled replacement of wear parts like pumps and fans)	20 years

4. Benchmarking

The following table gives an overview of selected data for the energy storage technologies considered in the present report. The data are excerpts from the respective technology sections above. Further details can be found in those sections.

Property / Technology	Flywheel	Battery	CAES	Hydro	Supercap	Hydrogen	SMES
Start up time / response time	Instant	Instant	Few seconds	Few seconds	Instant	Seconds (if warm and running)	Instant
Ramp time - % of power capacity per second	25 %	Programmable	0.2 (100% in 14 min)	4 % (50% in 12 sec)	Programmable	0,05	Very high
Cyclability (with reference to the needs described in Section 2) and influence on lifetime	125000	10-20,000	Capacity independant of cycling	Capacity independant of cycling	Millions	Cycles to 80% capacity: thousands	Unknown
Round cycle efficiency (electricity out over electricity in), %	85%	85% (Li-ion based)	80	75-85 %	0,9	0,35	Unknown
Power capacity	100 kW - modular	MW on modular base	Multi MW	Multi MW	Up to 100 kW unit available	Modular	Variable
Energy capacity	25 kWh in 100 kW unit	MWh on modular base	Depends on reservoir	Depends on reservoir	300 kWh in unit	Modular	Variable
Investment, EUR per kW	2200 EUR/kW	300-450 EUR/kW	750	800-1000	250	3500 (FC) and 230 (EC)	1134
Investment, EUR per kWh	8800 EUR/kWh	400-1500 EUR/kWh	10	80-100 EUR/kWh	6000	n.a.	90 kEUR/kWh

5. Conclusions

Ancillary services to the power system are likely to become still more important for grid stability as intermittent energy sources penetrate to higher degrees and eventually cover the entire demand. As mentioned above the US Department of Energy has estimated that for every GW of wind power capacity installed in a system, 17 MW of spinning reserves must also be added to account for the system´s variability.

Crucial properties of storage technologies, which provide ancillary services, are speed, ramp rate and capacity. The speed at which the service can be deployed must at least meet the requirements given by the TSO for the particular synchronous area, but faster response is an attractive property, which can secure instantaneous balance of load demand and generated power. It has been suggested that the service provider should not only be paid for capacity, but also for the speed at which it can be deployed. This pay model may well be applied also in Denmark in the future

After screening the storage technologies included in the present project we have found that in particular two technologies come to the fore, namely flywheels and certain types of batteries.

Flywheels constitute a new technology for providing ancillary services. Flywheel technology is relatively expensive, partly because it is not yet produced at large scale, but on the other hand show very attractive properties concerning response rate and cyclability, i.e. no loss of performance even after many thousands of cycles independent of depth of charging/discharging.

Risø DTU already has experience with one type of large, stationary battery, the vanadium flow battery, which has shown an excellent ability to respond rapidly to demands for charging and de-charging. The flow battery has worked finely and has reacted to demands (charging as well as discharging) with extremely fast the rate, limited only by the power electronics (detailed results are reported in Final Report for ForskEL project no. 6555). However, other types of batteries may show better economy, life time or cycling properties. Lithium-ion batteries with high power capacity has matured during the last years, supported amongst other by penetration of hybrid electrical cars. Hybrid car batteries have characteristics and battery life time similar to the properties required for an energy storage device performing ancillary services. Certain types of lithium ion batteries, with the right combination of anode/cathode materials, show very promising properties with regard to cyclability, equal charge/discharge rate and high electrical efficiency.

In that view, and based on the different usage patterns in the two synchronous areas of Denmark, the recommendation of the present project is to purchase, install and operate two different storage technologies – flywheel based energy storage and lithium-ion battery energy storage.

We recommend that on test basis a flywheel system, due to its outstanding cyclability, be operated in the Eastern Danish synchronous region DK2, where the frequency of calls for primary reserves is high according to Figure 4. Likewise we recommend a battery system to be operated in the DK1 region, where the frequency of calls is lower than in DK2, but still represents a considerable challenge for the energy storage system.

6. Proposed test system

Based on the conclusions above we recommend to purchase, install and operate two storage systems based on different - and to some extent competing – technologies: flywheels and batteries. The purpose will be to test and evaluate the use of the electricity storage technologies in the Danish power system, with respect to capability of providing ancillary services for the power grid. We propose to install systems which will be able to deliver 150-350 kW and for installation in the two different synchronous regions of Denmark (Western Denmark, DK1, and Eastern Denmark, DK2).

The recommended technologies each have their advantages and disadvantages depending on the operation pattern and control mode. The costs associated with degradation of batteries and the high initial costs of flywheels are central parameters for identification of the optimal technology. If operation requires many deep charge/discharge cycles, batteries are likely to degrade too fast and O&M costs will accordingly be high. On the other hand, if operation does not require deep charging/discharging, the higher capital cost of the flywheel may be prohibitive. These arguments are reflected above and are the reason that we recommend both technologies to be tested.

7. List of abbreviations used in the report

AACAES	Advanced Adiabatic Compressed Air Energy Storage
AC	Alternating Current
AGC	Automatic Generation Control
BMS	Battery Management System
BOP	Balance of Plant
C	Unit for battery charging rate. 1C is charging from 0 to 100 % in one hour
CAES	Compressed Air Energy Storage
CHP	Combined Heat and Power Plant
DC	Direct Current
DK1	Denmark west of Storebaelt
DK2	Denmark east of Storebaelt
DoD	Depth of Discharge
ENTSO-E	European Network of TSOs for Electricity
FDR	Frequency Regulated Disturbancy Reserve
FNR	Frequency Regulated Normal Operation Reserve
HVDC	High Voltage Direct Current
ISO	Independant Service Operator
LED	Light-Emitting Diode
LFC	Load Frequency Controlled reserv
PHS	Pumped Hydro Storage
RFI	Request for Information
SoC	State of Charge
SVC	Shunt-Connected Static VAR Compensator
TSO	Transmission Service Operator
UTCE	Union for the Coordination of Transmission of Electricity (now ENTSO-E)
VAT	Value Addded Tax

Appendix A

Request for information sent to potential battery suppliers

RfI: Request for information

Dear battery vendor,

Thank you for your interest in the project 'Fast Electrical STorage for Ancillary Services' (Acronym FESTAS) funded by the Danish transmission system operator (TSO) Energinet.dk.

Based on several discussions with the TSO and the research institute Risoe DTU, we have decided to not specify a complete energy storage system, but to look at key benchmark parameters for phase 1 of the project. If batteries prove competitive, we will select a number of battery vendors to participate in phase 2, where at least one small scale system will be demonstrated, combined with experimental characterizations of the selected cells.

Please select a suitable battery cell for the application from your product selection, the focus area is 15 minutes runtime. If needed for budgeting, please assume an energy-storage capable of delivering 25 MW. Preferred voltage level is < +/- 550V.

A complete response on this 'RfI' includes:

- Completed yellow fields in this RfI
- Datasheet of selected cell
- Information regarding typical battery module configuration and installation, voltage level, module size, limitations in series/parallel configuration, if available
- Please supply request information on 1.3 1.4 1.5 1.6.1.7.1.8 1.9 1.11. 1.12 on battery module level also
- List of reference customers / projects
- Please respond before week 32

Further explanation of the individual fields – see next page. Please complete the fields marked in Yellow.

	Units	Please complete
Company & cell information		
0.1 Company		
0.2 Contact person		
0.3 Selected cell		
Technical benchmark – cell level		
1.1 Cyclability @ 70% DoD cycling	Cycles	
1.2 Cyclability @ 10% DoD cycling	Cycles	
1.3 Roundtrip energy efficiency @ 1C / 1C or specified	%	
1.4 Shelf life @ room temperature	Years	
1.5 Specific power	W/kg	
1.6 Specific energy	Wh/kg	
1.7 Power density	W/l	
1.8 Energy density	Wh/l	
1.9 Energy loss / month as function of SoC	%	
1.10 Ramp time (if possible, please provide graph)	s	
1.11 Specific power for 30 seconds	W/kg	
1.12 Power density for 30 seconds	W/l	
Economical benchmark – complete battery installation		
2.1 Investment / MWh	$/MWh	
2.2 Investment / MW	$/MW	
2.3 Yearly operation and maintenance cost	$/MWh	

The fields explained:

1.1: Please specify number of 70% DoD cycles at 1C charge / 1C discharge rate, until 80% capacity remains. Please specify which SoC the cycle works within (eg. 15% - 85%). If data is not available, please specify under similar conditions for cyclability

1.2: Please specify number of 10% DoD cycling at 1C charge / 1C discharge rate, until 80% capacity remains. If data is not available, please specify under similar conditions for cyclability

1.3: Please specify 70% DoD cycle energy efficiency; preferably 1C charge/ 1C discharge. Note that efficiency is defined as: Discharge energy [Wh] / Charge energy [Wh] for single cell or module. Please state electrical energy only

1.4: Shelf life for selected cell, please specify boundary conditions for figures stated like temperature and state of charge. If available, please specify shelf life at 90% SoC, 50% SoC and 10 % SoC

1.5: Please specify specific power at continuous power for 15 minutes

1.6: Please specify specific energy for 1C discharge rate, or specify boundary condition for energy capacity

1.7: Please specify power density at maximum continuous power for 15 minutes

1.8: Please specify energy density for 1C discharge rate, or specify boundary condition for energy density

1.9: Please specify self discharge rate for selected cell or module. Energy loss can be stated as = Daily loss [Wh] / Cell capacity [Wh]. If only relevant for system, please specify. If significant thermal loss, please include both thermal and electrical loss in Daily loss [Wh]

1.10: Please specify ramp time from zero power to full power if applicable

1.11: Please specify specific power rating for 30 s in suggested battery installation with suggested cooling system, or supply data for battery module

1.12: Please specify power density rating for 30 s in suggested battery installation with suggested cooling system, or supply data for battery module

2.1: Please state price per MWh, included should be:

- Battery cells
- Required mechanical part for making battery modules
- Battery safety system (if applicable)
- Cabling between battery cells and modules
- Thermal management system (excluding A/C for building)

Assume that building is at room temperature (20°C) when estimating capital cost for thermal management system.

2.2: Please specify price per MW, with boundary conditions as in 2.1

2.3: Please specify operation and maintenance cost for:

- Battery cells
- Battery safety system (if applicable)
- Thermal management system (excluding A/C for building)
- Other

Further information:

If you have any questions, do not hesitate to contact:

Limited availability in Week 28-31.

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