ENERGY STORAGE SYSTEMS FOR UPS AND ENERGY MANAGEMENT AT CONSUMER LEVEL

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ABSTRACT

The penetration of renewable energy, such as photovoltaic and wind energy will have an impact on the grid structure and may cause grid stability problems. Distributed ESSs (Energy Storage Systems) in combination with advanced power electronics provides a solution for such problems. For these reasons the importance of UPS (Uninterrupted Power Supplies) and ESSs will increase in the near future. Commercially available ESSs beyond lead acid batteries offer alternatives for UPS and can introduce Energy Management at the consumer level. With this background a technical and economic evaluation is given on the options for ESSs with respect to the most important requirements for UPS and Energy Management at consumer level. The evaluated emerging ESSs include flywheels and supercapacitors for short time power and flow batteries, advanced batteries and systems based on compressed air for longer periods as alternatives to lead acid batteries.

INTRODUCTION

Both power utilities and large industrial power consumers look at ESSs (Energy Storage Systems) for load leveling and grid stabilization. Considerable research is aimed at enhancing or replacing existing ESSs with systems that are more cost effective to purchase, lower on maintenance, easier to monitor, more compact and more environmentally friendly. There are numerous options available and over the past decade, a number of technologies have been commercialized. The challenge is to pick the right technology for the target application whilst meeting constraints on cost and performance. ESSs are increasingly investigated for regulation from seconds to hours in electric power systems. Ondalow et al [1] have investigated the monetary value of ESSs for different battery technologies in the MW range and Nourai et al [2] have presented the reduction of T & D losses due to load leveling. Any storage capacity in the grid does not replace the requirement of UPS, which always has to be closest to the critical load. On the other hand UPS battery storage may support grid stability as long as the minimum required backup energy always remains guaranteed. NAS and flow batteries have been evaluated for systems including UPS and load leveling or peak shaving functionality [3,4]. Supercapacitors have been compared to commercially available flywheels as a compact alternative to lead acid batteries for UPS bridging applications [5].

Commercially available ESSs enable Energy Management at consumer level by purchasing and storing low cost electrical energy during off-peak hours and providing this stored energy into the load or grid during peak hours. Energy Management with ESSs gives financial benefits to the consumer, increasing grid stability and giving an environmental friendly alternative to the diesel generators; which have been used at consumer level as a peak shaving device for many years. With this background, the purpose of this work is to give a technical and economical evaluation of ESSs for UPS and Energy Management at consumer level. Up to now mainly lead acid batteries have been used, but different new ESSs are appearing on the market. As an example, experimental work and system analysis has been carried out on a sodium metal chloride system using lead acid batteries as the comparison benchmark.

ENERGY STORAGE SYSTEMS OVERVIEW

ESSs for short discharge times in the range of seconds to a few minutes include supercapacitors and flywheels. For discharge times in the range of minutes to hours, advanced batteries and compressed air hybrid systems are candidates. Advanced batteries cover the flow battery technologies (Vanadium redox flow, polysulphide bromide and zinc bromine), Sodium-batteries (Sodium Sulphur and Sodium Nickel Chloride) and ambient temperature batteries (Nickel metal Hydride and Lithium Ion). Figure 1 gives a first comparison of the different alternative energy storage systems analyzed; The Ragone plot gives the energy density versus power density, as well as typical discharge times of the different ESSs.

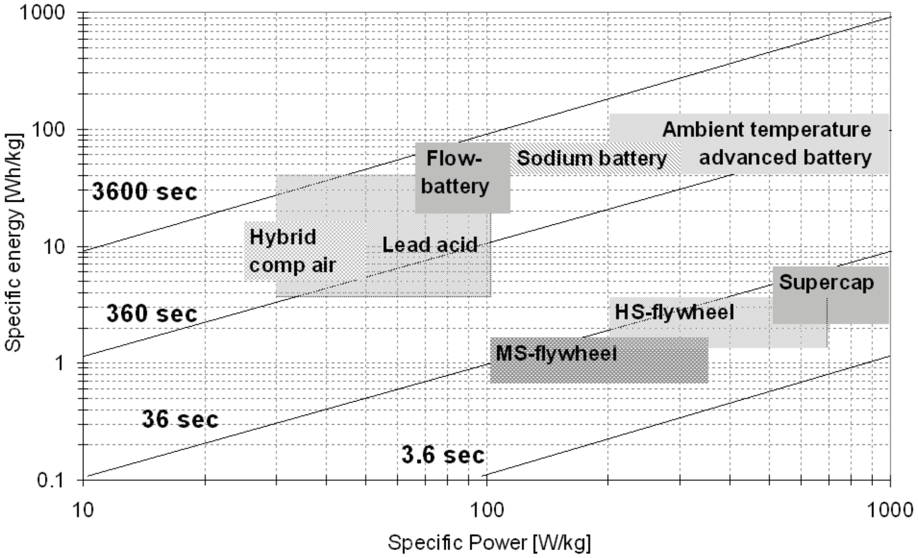

Figure 1 Ragone plot with the specific energy versus specific power, as well as the typical discharge time

TECHNICAL AND ECONOMIC EVALUATION

For UPS application, requirements such as: high reliability and availability, low initial cost, low operating (service, standby losses, etc.) and end of life recycling cost, long service life, low volume and weight (high specific power and energy), large ambient temperature range and low environmental impact are of prime importance. The purchase price together with the service cost and stand-by losses are some of the more important parameters for the economic evaluation of ESSs for standard UPS application. In the following sections the prices for the different ESSs are given in terms of purchase price per effective deliverable energy (1) and continuous deliverable power (2):

$/kWh = Purchase price/ deliverable energy (1)

$/kW = Purchase price/ continuous power (2)

For Energy Management a cycling time of up to hours is needed. In addition to the requirement listed above, high cycle life, high round trip efficiency and low energy storage costs are essential. The economic benefits of Energy Management using ESSs at consumer level should be evaluated in terms of the impact on energy fees, power fees and penalties. The benefits related to energy fees depend on the electricity price difference between low cost off peak and peak energy. The benefits related to peak power depend on the peak power demand reduction given by the ESS peak shaving capability. The power rates are dependent on local conditions and can vary from 5 to 25 $/kW per month (highest power demand averaged across a 15min period). Monitoring energy levels and injecting stored energy to shave these peaks may also lead to a reduction or elimination of forward penalties imposed to have peak demand levels available for the next calendar year. The cost per energy stored, which is more important for Energy Management applications compared to UPS alone, includes cycle life:

$/kWh*=Purchase price/(deliverable energy·cycles) (3)

Cycle life depends on several operating parameters including temperature, DOD etc. Here 80% DOD cycles at ambient temperature are assumed.

EXPERIMENTAL RESULTS

The most promising ESSs have been tested in combination with a UPS in order to assess their performance. The ZEBRA battery is presented here as an example of the experimental work being carried out.

The ZEBRA performance has been evaluated using two modules of type Z5-ML3C-557 in parallel and directly connected to the DC link of a General Electric SG50kVA double conversion UPS. The ZEBRA BMI (Battery Management Interface), which is designed for electric vehicle applications, has been modified in order to properly operate in combination with the UPS. Discharge experiments at different power levels have been carried out in order to evaluate the continuous deliverable power and deliverable energy as a function of the discharge time. In addition to the effective deliverable energy for a constant power discharge it is important to assess the temperature increase in order to properly design an adequate cooling system. For this reason temperature measurements have been taken during continuous power discharge. Figure 2 shows a constant power discharge of a single Z5 with 86 W/cell, 216 cells give 18.6 kW down to the minimum acceptable UPS Voltage of 396Volts.

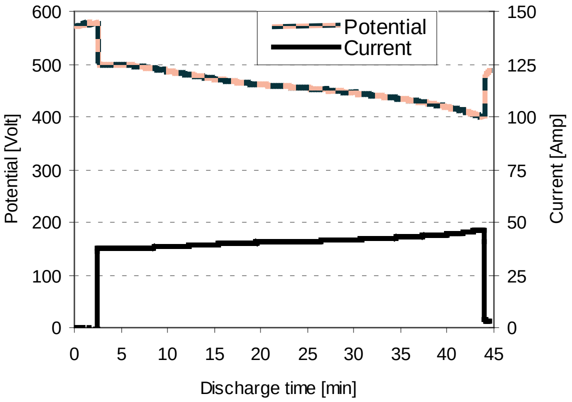

Figure 2 ZEBRA Z5 constant power discharge at 86 W/cell, 216 cells

In this case, as illustrated in figure 2, approximately 65% of rated energy has been delivered down to the minimum acceptable UPS Voltage of 396Volts with a temperature increase of 37˚C (from 300˚C to 337˚C) with air cooling on. Further experiments have been performed in order to evaluate the effect of the internal resistance and correlated voltage drops in case of battery load variation (UPS load variation, transfer bypass-inverter, etc.). Figure 3 shows the voltage drop of a ZEBRA Z5 during discharge at about 460Volts for a step load 18.6kW to 28.4kW compared to an equivalent VRLA (Valve Regulated Lead Acid) High Rate 33Ah battery string.

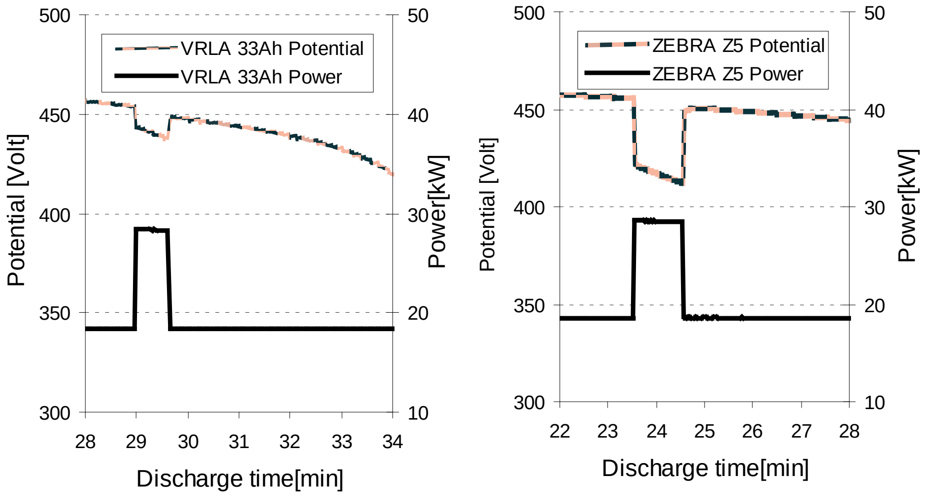

Figure 3 Step load comparison VRLA 33Ah (left) versus ZEBRA Z5 (right)

The higher voltage drop of ZEBRA compared to the correspondent VRLA battery is not a problem for the output voltage of the UPS, which is fully controlled by the inverter regulation. It is expected that further development of the ZEBRA battery will reduce the internal resistance and thus reduce the voltage drop.

The available continuous power for ZEBRA ML3C cell versus discharge time is given in Figure 4. This data should be referenced as key information behind any system design for the investigated applications.

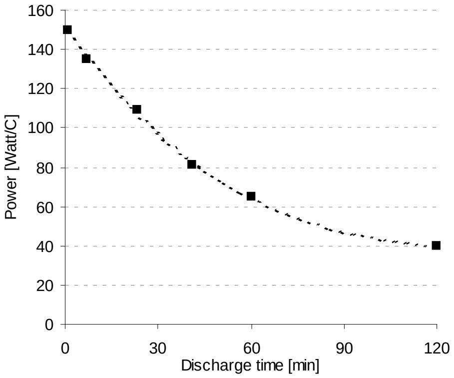

Figure 4 ZEBRA ML3C cell continuous power as function of discharge time

Using these results and the weight of the Z5 module of 180kg the specific energy in Wh/kg has been calculated as a function of the discharge time. Figure 5 shows the results compared to equivalent data for VRLA battery (High Rate 33Ah) and flooded lead acid battery (Ogi 1360 Ah).

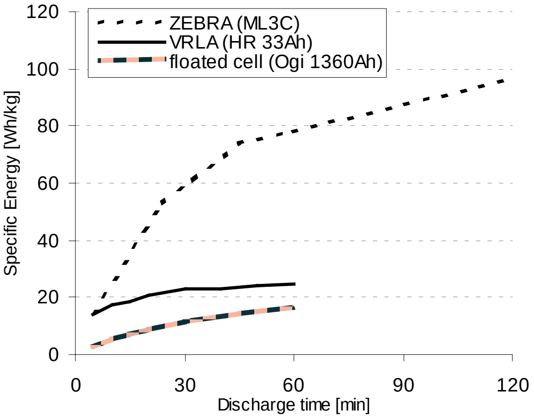

Figure 5 Specific energy as function of discharge time.

For a discharge time above 30 minutes, the specific energy of ZEBRA is a factor 3 to 4 lighter than the correspondent lead acid options. With the present price per rated energy of 750$/kWh [6] for the complete ZEBRA battery system the price in terms of deliverable energy as a function of the discharge time is calculated and compared to the equivalent value for flooded lead acid and VRLA batteries.

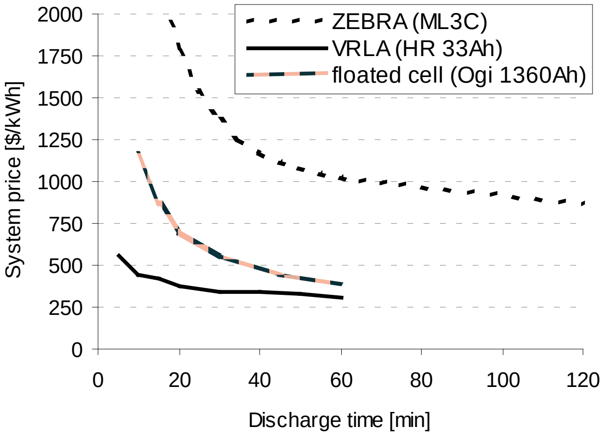

Figure 6 System price as function of discharge time.

For all analyzed ESSs, low prices are related to large discharge time and high prices to short. It is obvious that the mature lead acid battery technology is still more economic than ZEBRA but this is expected to change because of the low raw material cost of the ZEBRA system. For a comprehensive economic evaluation, in addition to the purchase price, the operating costs (service, stand-by losses, ventilation, etc.) should be considered.

ESSs FOR SECONDS DISCHARGE TIME

ESSs for less than a minute of discharge time fall under the category of bridging applications and typically require very fast high power responses. Flywheels, super capacitors and superconducting magnetic energy storage (SMES) are the options here, though SMES is suited only for megawatt scale applications and is not further considered.

A. Flywheels

Flywheel Energy Storage Systems (FESSs) couple a rotating mass with power electronics. The energy stored in the flywheel is governed by the equation $Ec \propto M \cdot R^2 \cdot RPM^2$. Increasing the radius and/or speed increases the stored energy, but will also increase the mechanical stress on the material and require more sophisticated bearings. As such, three types of flywheels are available on the market: Traditional Low speed (about 1500 RPM), Medium Speed flywheels (up to 10000 RPM) made of steel and High Speed flywheels (25000-100000 RPM) using composite material.

Traditional Low-Speed Flywheels have a very large mass and are directly coupled to the generator and motor of an engine generator set. They have a relatively low speed (about 1500 rpm) maximum autonomy in the range of seconds and are supported by conventional bearings. These systems are large, noisy and require regular and extensive maintenance. Due to the tolerances of the voltage frequency, only about 5% of the stored energy can be used.

Medium-Speed Flywheels operate at speeds up to 10.000 RPM. These systems are considerably larger than their high-speed counterparts for the given amount of stored energy. However, the flywheel is made of steel instead of composite materials, so is still slightly cheaper to manufacture. Conventional bearings with magnetic support are used to support the large rotor weight, but only a partial vacuum is needed to maintain low frictional losses. These losses combined with the excitation losses result in a stand-by power, which is roughly double that of the high-speed storage system. Most medium speed flywheel systems utilize either a single-stage IGBT or a rectifier/inverter for power transfer. Some operate with an induction or mechanical coupling instead of this DC interface. This induction coupling can be used to correct for changing rotational frequency, whereas the mechanical coupling must compensate through power electronics acting as a three-phase exciter winding in the generator. Overall, the advantage of the medium-speed flywheel storage system is a rugged design with mature and tested components. The greatest advantage of flywheels compared to batteries is the ability to predict the amount of remaining energy with pinpoint accuracy. The expensive and difficult implementation (high-precision settings) and the relatively high stand-by losses are the major disadvantages of these systems. For this mature technology, significant future improvements in terms of performances and cost reduction are not anticipated.

High-Speed Flywheels operate above 25.000 rpm. The rotating mass, weight and dimensions are relatively small. To reduce friction, the rotor runs in a vacuum and is supported by magnetic bearings. The output frequency of the synchronous generator is in the kilohertz range. A power electronic rectifier/inverter set is connected at the output of the generator. The energy is injected at this point into the DC link circuit of the UPS. The power electronic converter is necessary to correct the large voltage swing at the generator terminals over the speed range; the generator itself is unregulated. The advantages of the high-speed flywheel are its compact size for a given amount of power delivered. Systems suitable for UPS applications are already available. Less expensive materials are required to reach more competitive cost.

B. Supercapacitors

Supercapacitors (also called ultracapacitors) are energy storage devices with functionality somewhere between a battery and a conventional capacitor. The energy is stored in the electric field of high surface area electrodes, leading to rapid transport of charges and therefore high power capabilities. The charge and discharge processes are highly reversible and do not require electrode reactions, therefore leading to high cycle life. The stored energy of the electric field ($E=\frac{1}{2}\cdot C\cdot U^2$) is derived from the capacitance and the applied voltage. The operating voltage of a cell is just a few volts (up to 3 volts). With cells connected in series modules operate at some hundred volts. The voltage distribution between the cells depends on the tolerances of capacity, leakage current and internal resistance. Different passive and active electric and electrochemical methods have been developed to control the voltage equalization between cells and the over-voltage of single cells. There are two types of supercapacitors: double layer capacitors and pseudo-capacitance based supercapacitors, depending on how the capacitance is formed. A hybrid supercapacitor is a combination of the two basic types.

Double layer capacitors consist of two electrodes, a separator and an electrolyte. A capacitance called the double layer capacitance arises at interfaces between the solid electrode surface and the liquid electrolyte. The electrode materials in current focus are metal oxides, carbons and conducting polymers. The electrolyte may be of the solid state, organic or aqueous type depending on the application. Electrochemical capacitors are based on pseudo-capacitance; the charge transfer and reactions between the electrolyte and the electrodes are the main energy storage mechanism. The charge transferred is highly voltage dependant, leading to the pseudo-capacitance also being voltage dependant. The capacitance of pseudo-capacitance material is higher than the carbon based materials.

Hybrid capacitors are fabricated with one electrode of a double-layer material and the other electrode of a pseudo-capacitance material. These capacitors have higher energy density than the conventional double layer capacitors.

Considering the technical maturity, wide temperature range (–25 to 65˚C), low standby losses and low environmental impact (no use of heavy metals), carbon based double layer capacitors are the most interesting and promising devices for high power low energy storage applications. The outlook on super-capacitors is that, with increasing volumes (mainly from the automotive and automated production sectors) the price is expected to come down in the near future.

C. Comparison of ESSs for seconds discharge time

In Table 1 the performance characteristics and prices of the most promising ESSs for less than a minute discharge time are compared to those of lead acid batteries.

TABLE I ESSs Options for seconds discharge time

	Lead Acid	HS Flywheel	MS Flywheel	Supercapacitors
Service life [year]	5-20	20	20	>10
Charge/Discharge cycles	300-1000	50000-300000	50000-300000	> 500'000
Total AC/AC efficiency [%]	75-85	90	90	85-95
Operating temperature [°C]	10 to 30	0 to 40	0 to 40	-25 to 65
Typical back-up time	5-30min	10-30 sec	10-30 sec	10-30 sec
Continuous power [W/kg]	30-100	200-700	100-350	500-3000
Deliverable energy [Wh/kg]	8-25	1.5-4	0.7-1.5	2-6
Losses stand-by	very low	low	high	low
Predictive Monitoring	moderate	good	good	good
Modularity	very good	good	good	very good
Environmental impact	medium	low	low	low
Maintenance	1 check/year	1 check/5year	1 check/year	no
Purchase price [$/kWh][1]	300-1000	40000-50000	30000-40000	40000-50000
Purchase price [$/kW][2]	60-150	100-200	100-200	80-150
Energy storage cost [$/kWh*][3]	1.00-1.50	0.13-1.00	0.10-0.80	0.08-0.12

[1] Purchase price of complete system based on deliverable energy, see section III

[2] Purchase price of complete system based on continuous power, see section III

[3] Based on deliverable energy and 80%DOD cycles, see section III

The large ranges given for performance and price of lead acid batteries are related to the discharge time and to the type of device considered. Higher prices and better performance for lead acid are related to expensive flooded cells; low prices and inferior performance relate to inexpensive VRLA. Flywheels and supercapacitors offer a very compact option for large cycle short discharge time applications with an acceptable price, and offer an alternative to lead acid only for discharge time up to about 20 to 30 seconds. For larger discharge times, both flywheels and supercapacitors must be combined with others ESSs or with fast-start generating sets. Future cost reduction is expected for supercapacitors and high-speed flywheels with increasing production volumes. For medium-speed flywheel systems, with steel rotor, the potential for cost reduction is extremely limited.

ESSs UP TO HOURS DISCHARGE TIME

This section looks at energy storage systems suitable for power delivery up to hours for UPS and Energy Management at consumer level. Perhaps the largest choice of energy storage devices is available in this group. Only those technologies that look the most promising in near term are being analysed.

A. Systems based on compressed air

Compressed air is one of the cheapest methods of energy storage. However, the converter system based on turbines with fossil fuel injection raises environmental questions. Different sorts of hybrid ESSs based on compressed air without fossil fuel combustion have been investigated. One of the important results of this research work is the TACAS (Thermal and Compressed Air Storage) developed by Active Power, which is based on compressed air and thermal energy storage technology [7]. Advanced hydro-pneumatic storage systems using the so-called “liquid piston” principle based on near-isothermal compression and expansion exhibit important potential for cycling efficiency improvements and higher energy density [8, 9]. A HyPES (Hydro-Pneumatic Energy Storage system) with 10kW and 40kWh will be available soon [10]. Compressed air ESSs provide a 20 year life expectancy (considering regular maintenance), competitive size, low environmental impact (recyclable and non-toxic materials), good monitoring capabilities and competitive life cycle cost compared to lead acid batteries.

B. Flow batteries

Flow batteries are typically sized for their power and energy ratings separately, making them ideal for large scale application. The energy content depends on the quantity of electrolyte stored and the power depends on the size of the stack, which may be sized as each application demands. The flow batteries to be considered are Vanadium Redox flow battery (Redox) and Zinc Bromine (ZBR). Polysulphide Bromide (PSB) battery is suited only for multimegawatt scale applications and is not further considered.

In a Vanadium Redox Flow battery (Redox), vanadium, a stable abundantly occurring metal, is held in two ionic forms in a dilute sulphuric acid electrolyte solution. By connecting stacks of cells electrically in series any operating voltage can be obtained. The battery stack and power conditioning system capability will determine the power rating of the battery system while the energy rating is determined by the electrolyte concentration and dimension of the storage tank. For a given rating of operation the cost of additional energy storage capacity depends mainly on the cost of the additional electrolyte storage, this being a major advantage of such a system. The only moving parts in the system are the pumps that require maintenance. Vanadium Redox battery is promoted as a green technology since there are no established environmental effects due to the electrolyte or the stack. The battery system however has not been evaluated for field life and therefore the long-term cycle life and maintenance issues are yet to be ascertained. The future development in this battery is for large-scale systems. As of now this battery system is found to be more competitive for applications requiring a large storage period. There are many Vanadium systems in operation since 2000 [11, 12].

Zinc Bromine System (ZBR) is based on the reaction between two commonly available chemicals, zinc and bromine. All battery components are made from a bromine inert plastic. The zinc/bromine battery uses electrodes that do not take part in the reactions but merely serve as substrates for the reactions. There is therefore no loss of performance, as in most rechargeable batteries, from repeated cycling causing electrode material deterioration. When the zinc/bromine battery is completely discharged all the zinc plated on the negative electrodes is dissolved in the electrolyte and again produced the next time the battery is charged. In the fully discharged state the zinc/bromine battery can be left indefinitely. Zinc Bromine systems are well suited for long duration storage applications. Several field trials of this battery have been conducted. A key installation is the 400kWh installation in Detroit Edison [13].

C. Sodium batteries

Sodium Sulphur Battery or NAS technology is based on a reversible reaction between Sodium and Sulphur in combination with a β``-alumina electrolyte. For good sodium ion conduction in this solid electrolyte, the operating temperature of the cell is maintained at 300˚C to 350˚C. The predominant features of the NAS battery are high-energy efficiency, long cycle life >2500 and low cost by large cells. The battery system was developed to require minimal field maintenance. The NAS battery system is designed for a 7 to 8 hour charge or discharge and comes in two forms for peak shaving and power quality applications, basically differing in the way the cells are arranged and the method of protection. The system is modular with 50 kW/360 kWh units. A short peak power of up to 150 kW is possible if the reduction of available energy can be tolerated. One of the largest installations of this battery deployment is a 6000kW-48000kWh load leveling station at TEPCO [3]. NAS batteries are mainly used for grid control.

Sodium Metal Chloride Battery or ZEBRA (Zero Emission Battery Research Activity) battery is also a high temperature system, operating at around 270˚C to 350˚C. The chemical reaction in the battery converts common salt (sodium chloride) and nickel to nickel chloride and sodium during the charging phase. During discharge, the reaction is reversed. Each cell is enclosed in a robust steel case. A ZEBRA battery is designed for a 2 hour discharge with peak power capability as required for EV operation. A complete system including the battery box with cells, thermal management system and electrical management system is offered by the supplier. ZEBRA cells can be connected in series or parallel in almost any combination, thereby permitting large and small battery systems to be designed using the standard cell. The major features of the battery are high energy efficiency, high power and energy density, long life and intrinsic safety. As the battery system is isolated from ambient conditions as in the case of NAS battery, it is insensitive to ambient temperature changes making it an attractive proposition for usage in all climates. This promising technology, though initially developed for electric vehicle applications, is currently evaluated for various other uses [14]. Present development work is dedicated to a reduction of the internal resistance and cost [15].

D. Ambient temperature advanced batteries

The Nickel Metal Hydride (NiMH) battery was first brought into production in the late 1980s as an environmentally more acceptable replacement for nickel cadmium batteries in consumer applications. Because the special alloys used in the electrode have a higher H2 density, the volumetric energy density of metal hydride electrode is about 50% higher than the cadmium electrode. Like the Ni-Cd battery, the NiMH battery uses a nickel-oxyhydroxide positive electrode and an alkaline electrolyte, but the active material in the negative electrode is a hydrogen-absorbing metal alloy instead of cadmium.

In Lithium Ion (Li-ion) cells on the other hand, the current is carried by lithium ions from the positive electrode (cathode) to the negative electrode (anode) during charging, and from negative to positive during discharging. Lithium metal is intercalated in carbon on the anode side and reacted with metal oxides on the cathode side in order to overcome safety concerns. The ions are small and reside within the crystal structure of the electrode materials. This battery chemistry offers high specific energy that is being utilized effectively in low power consumer applications. Nickel Metal Hydride and Lithium batteries are finding prominence in the automotive industries but are limited in application mainly due to the high cost of these chemistries. With large-scale usage of the high power and high energy versions, the cost barrier could be lowered in future and they would become more viable for large storage systems. The demands of advanced battery management and thermal management systems to maintain the temperature of these batteries within limits adds considerably to their overall costs [16].

E. Comparison of ESSs up to hours discharge time

In Table 2 the performance characteristics and prices of the most promising ESSs with discharge time of minutes to hours are compared to those of lead acid batteries. Advanced ESSs based on compressed air are not considered for this comparison because they are still in the development phase.

TABLE II ESSs Options for discharge time up to hours

	Lead Acid	Flow battery	Sodium Sulphur	Sodium Nickel Chloride	Nickel Metal Hydride	Lithium Ion
Service life [years]	5-20	15-20	15	>12	10	<10
Charge/Discharge cycles	300-1000	2000-5000	2500-4500	>1200	800-1200	1000-3000
Total AC/AC efficiency [%]	75-85	70-80	80-85	80-90	65-70	90-95
Operating temperature [°C]	10to30	0to50		-40to50	-20to40	-20to45
Typical back-up time	5-30min	hours	hours	>20min	minutes	minutes
Continuous power [W/kg]	30-100	80-100	10-100	40-120	200-600	200-1000
Deliverable energy [Wh/kg]	8-25	20-80	50-80	40-80	40-80	60-140
Losses stand-by	low	moderate	moderate	moderate	moderate	moderate
Predictive Monitoring	moderate	good	moderate	good	moderate	moderate
Modularity	very good	moderate	good	good	good	good
Environmental impact	medium	low	low	low	low	low
Maintenance requirements	moderate	moderate	low	low	moderate	moderate
Purchase price [$/kWh][1]	300-1000	500-2000	450-1500	750-3000	1200-1400	1500-3000
Energy storage cost [$/kWh*][2]	1.00-1.50	0.10-1.00	0.10-0.60	0.60-2.00	1.00-1.75	1.50-3.00

[1] Purchase price of complete system based on deliverable energy, see section II

[2] Based on deliverable energy and 80%DOD cycles, see section III

The large variation of storage price indicates the infant state of the development for new technologies. For all ESSs the lower purchase prices are related to large discharge time in the order of several hours and the higher prices are related to short discharge time in the order of minutes. As for table 1 the large ranges given for performance and price of Lead Acid are also related to the type of device considered.

The NAS is most advanced but sodium metal chloride has the future potential for lower cost if the nickel is replaced by iron. NiMH battery technology is regarded as a mature technology; which is installed in millions of hybrid electric vehicles. It has moderate specific energy but high power capability. The cost per kWh has reached a stable level and further reductions cannot be expected for future because of the cost of material required.

This is fundamentally different for Li-Ion batteries; which have reached a mature state for consumer size units based on Li-CoO2 chemistry. New chemistries are under development with several hundred million $ R&D budgets for future electric and plug-in hybrid electric vehicles. Therefore new results can be expected within the next 5 to 10 years. Currently it is very difficult to estimate a future price level as new inventions will be required to reach the targets of the automotive industry.

Flow batteries have reached the stage of demonstration projects, the costs of the technology will decrease as soon as the technology becomes available as a commercial product.

OPTIONS FOR UPS AND ENERGY MANAGEMENT AT CONSUMER LEVEL

A. UPS

Modern UPS, especially for large installations like data centres, require a discharge time of less than 15 minutes. Flywheels and double layer capacitors have acceptable price and efficient built-in monitoring capabilities and offer a good alternative to lead acid batteries for riding out power quality problems lasting up to 20 seconds. For specific UPS applications with frequent short duration outages, both alternative storage systems could also be used in parallel to batteries to extend their life. For typical back-up time of several minutes, these ESSs have to be combined with fast-start generating sets with the assumption that the generator will run up to full output power within 15-20 seconds. Many users are reluctant to adopt this approach, since there is no second chance to start the generating set should the first attempt fail.

Both Nickel metal hydride and Li-ion are currently too expensive for UPS applications. Only Li-ion with further development related to new chemistries might reach the required cost level. Sodium Metal Chloride batteries with expected future cost reduction have an important potential as lead acid flooded cell alternative. Other options like NAS and Flow batteries are designed for discharge time in the order of hours and for this reason are not a suitable alternative for a standard UPS application.

B. Energy Management at Consumer Level

ESSs for Energy Management at consumer level require discharge time up to hours. For this application, both flywheels and supercapacitors have to be combined with others ESSs.

As for UPS application, Nickel metal hydride and Li-ion are currently too cost-prohibitive. Sodium Metal Chloride batteries are an interesting alternative for discharge time in the order of minutes to hours. NAS and Flow batteries, with price projections for large volume production below 300$/kWh, are a viable option for discharge time in the order of many hours. Advanced energy storage systems based on compressed air, still in the development phase, could be a future low environmental impact alternative if they are able to reach a competitive life cycle cost.

The economic benefits of Energy Management using ESSs at consumer level need to be evaluated in terms of the impact on energy fees, power fees and penalties. The benefits related to energy fees depend on electricity price difference between low cost off peak and peak energy. Energy Management using ESSs at consumer level becomes economically interesting when the difference in the grid peak energy price versus low-cost off-peak price is close to the storage cost as defined in section III. A preliminary evaluation of ESSs for Energy Management applications is based on the energy storage cost as a function of the discharge time. Figure 7 gives an overview of the current storage cost for the most promising ESSs options.

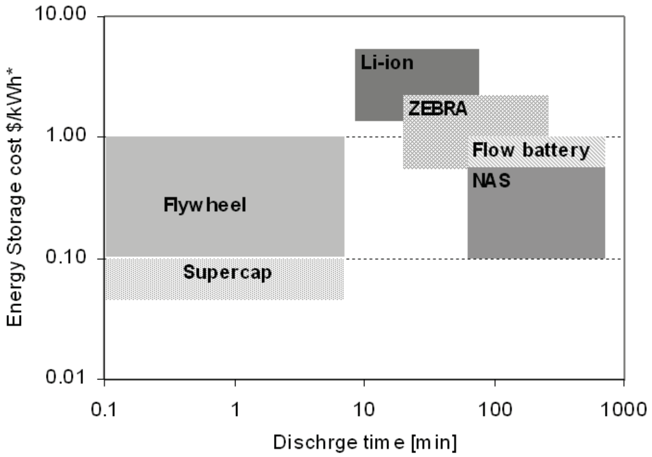

Figure 7 Energy storage cost as function of the discharge time

For the majority of the storage systems analyzed, further technology progress is expected; this will lead to lower storage costs. As an example, for large volume production the ZEBRA technology can reach a price of rated energy below 200 $/kWh [17] and a cycle life of 4000 cycles has been demonstrated in laboratory tests. These data indicate a storage cost level of 0.05 $/kWh to be possible.

For a more comprehensive economic evaluation in addition to the impact of power fees and penalties; the initial system purchase price as well as the operating costs have also to be taken into consideration.

As an example, options such as supercapacitors and flywheels have relatively low energy storage costs, but due to the very large system purchase price in terms of $/kWh, they are economically attractive only for short discharge time applications.

CONCLUSION

Decentralized ESSs in combination with advanced power electronics enable Energy Management at consumer level, giving financial benefits to the consumer and increasing grid stability.

An economical evaluation of Energy Management using ESSs at consumer level should be based on system purchase price and operating cost as well as on the impact regarding energy fees, power fees and penalties. The purchase prices as well as the most important performances of ESSs have been evaluated as a function of the discharge time for UPS and Energy Management at consumer level.

In order to deliver the required energy for both investigated applications, flywheels and supercapacitors have to be combined with others ESSs or with fast-start generating sets. Li-ion and especially Sodium Metal Chloride batteries with an expected future cost reduction have an important potential as lead acid flooded cell alternatives. NAS and Flow batteries are an interesting option for Energy Management at consumer level; this functionality could possibly be integrated in the next generation UPS.

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