ELECTRIC POWER RESEARCH INSTITUTE

Technology Review and Assessment of Distributed Energy Resources

Distributed Energy Storage

1012983

Technology Review and Assessment of Distributed Energy Resources

Distributed Energy Storage

1012983

Technical Update, February 2006

PRI Project Manager
D. Rastler

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1395 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

TIAX LLC

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This report was prepared by

TIAX LLC
15 Acorn Park
Cambridge, MA 02140-2390

Principal Investigator
W. P. Teagan

This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

Technology Review and Assessment of Distributed Energy Resources: Distributed Energy Storage, Palo Alto, CA: 2005. 1012983.

PRODUCT DESCRIPTION

The investigators reviewed, benchmarked and assessed the current status of emerging battery technologies for distributed energy storage (DES) as it applies to market applications addressing residential, commercial, and light-industrial buildings, and the prospects for significant market impacts with in the electric utility sector over the next 5-7 years.

Results & Findings

New energy storage developments targeted to HEVs, portable, and stationary applications may improve the viability of batteries as an option for distributed energy storage. In particular, developments in both nickel metal hydride (NiMH) and lithium-ion batteries for EVs and HEVs have increased calendar and cycle life while using potentially lower cost materials. As a result of these developments and the economies of scale and competitive intensity of portable and HEV markets, the prospects of battery energy storage for commercial building applications may also be improved. Another battery technology not previously considered by EPRI, ZEBRA a high temperature battery, may also be another option offering long life and the potential for low cost while leveraging the economies of scale from heavy duty transportation markets. Over the next 5 - 7 years these technologies could surpass those currently under consideration by the utilities such as sodium sulfur and flow batteries.

Challenges & Objectives

The results of this investigation will be of interest to those in the electric utility industry responsible for:

- Strategic and corporate technology planning
- Anticipating customer demand and the associated implications for generation, transmission, and distribution requirements;
- Ensuring a reliable and high-quality power supply to customers; or
- Integrating DES within their service areas.
- Regulatory policy

Periodic review and assessment of advances in batteries is important to understand if improvements in technology and economics have increased the commercialization prospects of batteries for energy intensive loading leveling and peak shaving applications. If promising, the utilities can develop strategic partnerships to direct new battery developments to the requirements of heavy duty cycle energy storage in large scale stationary applications.

Applications, Values & Use

Emerging developments in battery technology may allow utilities to implement heavy duty deep cycle energy storage systems for loading leveling and peak shaving, thereby benefiting both end-users and utilities. Cost effective DES could allow end-users to lower their electricity cost while utilities could use DES to better manage and plan distribution assets, improve load factor, and increase overall reliability.

EPRI Perspective

The findings in this study indicate that DES technologies in the pipeline today could significantly impact the electric utility business potentially within the next 5-7 years. Advances in battery technology could allow DES to serve and impact markets for residential, commercial, and light-industrial end-users enabling distribution utilities to leverage these assets and monetize their value through both regulated and non-regulated business models. No other technology offers the potential to have as significant an impact to utilities in this timeframe. Growing sales of hybrid electric vehicles may also accelerate the availability of DES systems for utility applications.

While this report focused on DES technology, continued research is needed to evaluate the societal benefits and how utilities can make money with decentralized energy storage systems in general including their combination with energy efficiency, load management, DG, and distributed renewables. In 2006, EPRI will conduct research to quantify the value and business case(s) for a “distributed utility” in both competitive and de-regulated markets. EPRI also plans to accelerate the availability of DES systems through its energy storage research program.

Approach

The investigators reviewed and benchmarked the development status of battery technologies with a focus on advanced batteries being developed for hybrid electric vehicle markets, including projected developments over the next 5 – 7 years, and related analyses of life, cost, energy savings, and economics. Sources and analyses included:

- EPRI’s 1999 Assessment of Distributed Resource Technologies, which was written by many of the same investigators who conducted the current investigation. The 1999 study served as a baseline for the current investigation;
- Recent battery conference proceedings and information from battery developers;
- Selected interviews with technology developers; and
- Limited additional analyses completed as part of this investigation and not otherwise published.

Keywords

Distributed energy storage
Battery energy storage,
Distributed energy resources
Decentralized energy

EXECUTIVE SUMMARY

Introduction

Distributed energy storage (DES) refers to the placing of electric storage capability at or near the point of electricity consumption (commercial buildings, etc). By so doing, the storage capacity can have multiple, interrelated, benefits to end-users, T&D companies, and to generating companies:

- Ensures a higher level of power quality and reliability
- Provides support for the T&D system (assuming dispatch of capacity during peak periods)
- Provides potential for energy cost arbitrage by purchasing lower cost off peak power for use during high cost peak periods
- Enables generators to run large coal and natural gas units base load to avoid costly cycling issues
- Enables distribution utilities to manage peak demand, increase load factor, and increase end-user reliability.

No single technology could have a larger impact on the utility industry if widely implemented - so doing would result in more efficient utilization of current generation and T&D assets, improve reliability, and result in increased power sales. However, despite numerous demonstrations widespread implementation of DES has not happened.

For commercialization in DES applications, battery technologies will have to meet several criteria relative to such critical issues as

- Life (cycle and calendar)
- Installed cost (battery, power and interconnect circuitry, and installation)
- Maintenance cost

Other factors will include round-trip efficiency, weight and volume, and reliability.

Earlier analyses (Zogg) indicated that the economics of DES were still marginal in most applications (but often close to a range of interest) given the combination of technology assumptions and electric rate structures used. There are, however, significant advances taking place in battery technologies at a pace not before experienced in this industry because of increasing demands for energy, power, and safety from portable and hybrid electric vehicle

(HEV) applications. It should be noted that many of these developments are taking place offshore - particularly in Japan.

Demonstration of large DES systems (e.g., 2-50 MW and 2-15 MWh) has involved lead-acid (PbAc), nickel cadmium (NiCd), sodium sulfur (NaS), and flow battery technologies. These demonstrations have been co-operative cost shared programs involving utilities, state and federal agencies, and technology developers. New demonstrations of NaS and flow batteries are planned for this and next calendar years. Results of these demonstrations will provide additional information and confidence on the performance, maintenance, and life attributes of these technologies. Consequently, in this study the investigators focused their efforts on newer emerging technologies.

For the purposes of this study we considered a user or utility owned storage system which is charged at night using "low cost" off peak power and discharged as appropriate during the day to reduce costly demand charges and the use of high-cost peak power and/or provide distribution system benefits. In this type of application, the charging and discharging processes could each typically occur over 10 to 14 hours. The objective of this type of system would be to reduce peak daytime electricity usage and peak loads to reduce overall energy costs.

Objectives

In this study, key objectives included

- Assessment of recent and ongoing developments in battery technologies which are the most likely have commercial importance in a 5 to 7 year time frame and could significantly enhance the prospects for distributed storage and DER in general
- Development of a set of criteria to screen traditional and emerging technologies, such as life and cost targets from high level economic analysis of energy storage for commercial buildings
- Recommendation of technologies for further consideration and suggestion of next steps

Key Findings

Requirements

A high level economic analysis of distributed energy storage application yielded the following requirements:

- A 10 year life with a cycle life of greater than 2600 cycles is required to have reasonable capital and battery replacement costs – this is an end-user requirement.
- An OEM battery cost of $150-300/kWh is needed to have widespread economic potential.
- Negligible maintenance costs are important which implies a sealed battery chemistry.

In addition to these requirements a battery chemistry that has minimal thermal management requirements is highly desirable to minimize the capital and maintenance cost of an environmental enclosure.

Energy storage economics will be influenced by local day/night power costs differentials and the ability of local utilities to monetize and realize the T&D benefits and/or central plant investment benefits from the energy storage system.

The review gave special attention to emerging battery technologies coming out of portable or HEV markets which will have the benefit of:

- Significant economies of scale in the production of raw materials and cell components/materials due to market size
- Competitive intensity to drive technology innovation and cost reduction
- Significant growth in both portable and HEV markets due to expansion of applications and the economic expansion of China and India

Lithium ion batteries dominate the large portable market. Portable markets are anticipated to be the largest market for advanced batteries in the time frame of this assessment.

Battery Technologies

The screening process indicated that most of the widely used battery chemistries are unlikely to meet the stringent cost/performance requirements of the target applications, specifically:

- Lead-acid (PbAc) batteries are a mature technology with relatively low cost but with inadequate calendar and cycle life for daily deep discharge energy storage applications.
- Nickel cadmium (NiCd) batteries, another mature technology, offer high power performance, abuse tolerance, and long life, but suffer from an inherently high purchase cost structure due to extensive use of costly materials.
- Nickel metal hydride (NiMH) used in portable applications and now dominant in HEV applications continue to advance and need to be monitored. Specifically their ability to meet deep cycling applications and cost targets need to be benchmarked and monitored
- Flow batteries use several chemistries including vanadium redox, zinc bromine, and bromide polysulfide. Flow batteries combine the characteristics of fuel cells (anode and cathode electrodes that provide surface area for the reactive components), size of the reactant storage determines the capacity (energy) of the battery, and of rechargeable batteries because the active materials are regenerated. Flow batteries have the maintenance characteristics associated with circulating fluid systems and require more space because of their lower energy density. Operating experience with flow batteries through planned demonstrations and product sales will provide the real world data on operating costs and product life needed to judge the economics of flow batteries for DES.

The battery chemistries that show the most potential of meeting application needs were sodium sulfur (NaS), lithium ion (Li-ion), nickel metal hydride (NiMH) and sodium nickel chloride ($NaNiCl_2$, ZEBRA).

NaS:

Sodium sulfur (NaS), a high temperature battery, has been under development by NGK (Japan) for stationary applications. NGK has a large number of demonstrations and project viable costs for high volume production.

Due to the ongoing demonstrations of NaS this report focused on the status and potential of lithium ion, nickel metal hydride (NiMH) and ZEBRA batteries. However, a follow-up benchmarking of NaS should be conducted after the on-going utility demonstrations.

Lithium-Ion

Li-ion is a potential promising candidate for energy intensive DES applications, reasons for this assessment include:

- Li-ion technologies have experienced significant advances in performance driven by the demands of the ever growing portable markets for digital electronics and the emerging HEV market. Li-ion dominates the portable small cell markets and we anticipate will begin to displace NiMH in HEV in the next 3-5 years. Li-ion material developments are increasing the power, energy, life, and safety of cells while reducing cost.
- Technology advances are also driven by the competitive pressures of major battery developers in Japan and Europe. Emerging companies in Korea and China are developing technology to become competitive. In the US, one company Valence is introducing one of the new technologies that might be suited for stationary applications.
- Li-ion utilizes lower cost materials than nickel based batteries and these may lead to costs compatible with the requirements of DES. However, Li-ion batteries require more electronics and safety devices and the cost of these must be balanced against the lower cost of cell materials.
- Li-ion producers have started to introduce products for stationary applications. SAFT, an established battery company, recently introduced a product with a quoted life of 20 years and 3000 deep cycles. Valence, a startup, introduced another product with a rated life of greater than 10 years and 2000 deep cycles.

Sodium – Nickel Chloride (ZEBRA)

ZEBRA, a high temperature battery being commercialized by MES-DEA Sa, has been tested extensively in EVs and HEVs, but is relatively new to stationary applications.

- The life and projected cost of ZEBRA show the potential to satisfy the requirements for DES, however a more in-depth cost analyses is needed to better assess its potential for DES markets.
- With a cell failure mode of forming a short between the anodes makes high voltage strings of ZEBRA cells more potentially reliable than other battery technologies. This failure mode also leads to a safer battery than NaS.
- Even though only one developer is pursuing ZEBRA, heavy duty HEV markets have been targeted which may create economies of scale to bring down cost.

The attractive features of the ZEBRA technology have been recognized by potential users in Europe for heavy duty hybrid and electric vehicles and has led to increasing interest in the United States and Japan. This recognition is reflected by the technology being used in over 40 demonstrations involving well know organizations such as ABB, DaimlerChrysler, Fiamm, General Electric, ISE Corporation, and Rolls-Royce. Therefore, the attractiveness and market viability of the ZEBRA technology for DES applications needs to be followed and evaluated.

Nickel Metal Hydride (NiMH)

NiMH is well proven and finding applications in HEV and EV markets. While cycling data is limited, there is some evidence these systems show stable life beyond 2000 cycles.

- Leading Japanese companies (Panasonic, Toshiba, and Sanyo) dominate the market and continue to innovate this technology.
- The technology may also advance from research being done on hydrogen storage materials for fuel cell vehicle applications.
- Several smaller companies have emerged with novel NiMH designs such as ElectroEnergy.

For these reasons, the technology should be monitored and closely followed.

Gaps

Neither Li-ion or ZEBRA technology has been considered for larger scale stationary energy storage applications, consequently, cell and battery designs and the supporting electronics will have to be engineered for cost, reliability, repair, and safety. A gap in the NiMH technology is the cost of nickel. Overall DES battery designs including enclosures and environmental controls are needed to estimate the installed cost and maintenance requirements and to test performance and life in DES applications.

Developers with an interest in developing DES markets for their technology will have to be identified. For MES-DEA Sa, the DES market represents a large new opportunity and we would expect significant interest. On the other hand, Li-ion developers have portable, HEV, and UPS markets that are willing to pay higher prices than allowed by large scale DES. A business case will have to be presented that benefits both the battery developer and the utilities.

Recommendations

- Conduct in-depth industry discussions with developers and system integrators to assess their interest in stationary applications, the desire to engineer and produce high ampere hour cells, and their interest in more cost sensitive markets.
- Develop an independent view of MEA-DES manufacturing cost analysis of ZEBRA
- Conduct a bottoms-up system cost structure calculation including the battery, power and interconnect electronics, and installation costs.
- Conduct a more detailed assessment of the business opportunity for DES including the impact of rate structures, possible applications, market sizes/penetration versus cost/performance characteristics, and the role of the battery company, system integrators, and the utilities.

- Continue to follow and monitor efforts in advanced NiMH, and ultra capacitors. Conduct a bottoms-up cost analysis of NiMH to better assess the cost gap.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
BACKGROUND

Distributed Energy Resources

Both small to medium scale energy storage systems and small to medium scale fossil fuel options are included in EPRI's definition of distributed energy resources (DER). The overall topic of distributed energy resources (DER) received a great deal of attention during the 1990's and early 2000's as being a new model in how utility services would be provided in the future to commercial and light-industrial customers and potentially residential end-users as both a supplement and replacement for that provided by the traditional utility architecture. This perception was driven by a combination of dramatic changes in utility regulation, emerging technology developments, and the availability of relatively inexpensive natural gas. The potential benefits of DER were cited to include reduced annual energy costs to the customer (particularly when combined with CHP), increased levels of power reliability, and support of the T&D infrastructure.

The potential for DER has not been realized, with market development much lower than anticipated. The reasons cited include a combination of technology cost/performance shortfalls, regulatory uncertainties, grid interconnect issues, and lack of business models that can "monetize" both end-user and grid system benefits. Multiple studies by TIAX and others indicate, however, that the largest single reason for limited market success has been that, based on current technology, the economic case for DER based on energy cost savings considerations is not compelling in most applications. (Note: standby generators are not included in this discussion) Reasons for marginal economics include some combination of the following (with the relative importance depending on technology):

- Relatively high O&M costs (typically 1 to 3 cents/kWh) associated with commercially available technologies (much higher for developmental technologies)
- Modest electric generation efficiencies (typically 24% to 35%) that, combined with the retail cost of natural gas, significantly impacts the cost of power
- High capital equipment costs on an installed basis—due, in part, to a lack of standard packages (including interconnection)
- Unresolved uncertainties relative to emission/noise issues—particularly for IC engines

It is increasingly recognized that a large market for DER will depend on significant technology advances in modular fossil fuel based generation, energy storage systems and combinations of these. In energy storage technologies growing markets for portable electronics and HEVs are driving the development of improved batteries with higher power densities, longer life, and lower cost.

Energy Storage Technologies

Distributed energy storage (DES) refers to the placing of electric storage capability at or near the point of electricity consumption (commercial buildings, etc) By so doing, the storage capacity can have multiple, interrelated, benefits to end-users, T&D companies and to generating companies:

- Ensures a higher level of power quality and reliability
- Provides support for the T&D system (assuming dispatch of capacity during peak periods)
- Provides potential for energy cost arbitrage by purchasing lower cost off peak power for use during high cost peak periods
- Enables generators to run large coal and natural gas units base load to avoid costly cycling issues
- Enables distribution utilities to manage peak demand, increase load factor, and increase end-user reliability.

No single technology could have a larger impact on the utility industry if widely implemented - so doing would result in more efficient utilization of current generation and T&D assets, improve reliability, and result in increased power sales.

In 1999, the investigators undertook a top level analysis of the use of distributed energy storage as applied to commercial buildings on behalf of the DOE. The focus was on battery technology - however, both flywheels and reversible hydrogen cycles were also considered. This study quantified the critical importance of several issues when assessing the potential for distributed storage - these include:

- Round trip efficiency
- Capital cost of the storage subsystem
- Impacts of discharge levels and rates on capital costs
- Useful life (cycle life vs. level of discharge)
- Salvage value - recycling requirements
- The cost and efficiency of the power electronics required for a complete system capable of efficient charging and discharging in parallel with grid supplied power (note: this issue is often overlooked)
- The impacts of battery management controls and electronics

The DOE analyses indicated that the economics of electric storage were still marginal in most applications (but often close to a range of interest) given the combination of technology assumptions and electric rate structures used. There are, however, significant advances taking place in storage (battery and ultra capacitor) technologies at a pace not before experienced in this industry because of increasing demands for energy, power, and safety from lithium batteries in portable applications and hybrid electric vehicles (HEVs).

In this study, a key objective is to focus on recent and ongoing developments in battery and ultra capacitor technologies which are the most likely have commercial importance in a 5 to 7 year time frame and could significantly enhance the prospects for distributed storage and DER in general. Developments in these fields are driven by worldwide forces associated with portable equipment, and, increasingly, hybrid electric vehicles. It should also be noted that many of the developments are taking place offshore - particularly in Japan.

2
COST/PERFORMANCE REQUIREMENTS

Example Economic Analysis

The distributed storage architecture being addressed is indicated in Figure 2-1. In this system the storage is charged at night using "low cost" off peak power and discharged as appropriate during the day to reduce costly demand charges and the use of high-cost peak power. Typical load profiles for commercial buildings (Figure 2-2) and review of utility rate structures indicate that the charging process would typically occur over 10 to 14 hours and the discharge period over 10 to 14 hours. Every application will have unique energy storage sizing and operational strategies depending on building load characteristics, utility rate structures, and storage system operational strategy. The objective of system operation will be to reduce peak daytime electricity usage and peak loads to reduce overall energy costs (as indicated by example in Figure 2-3).

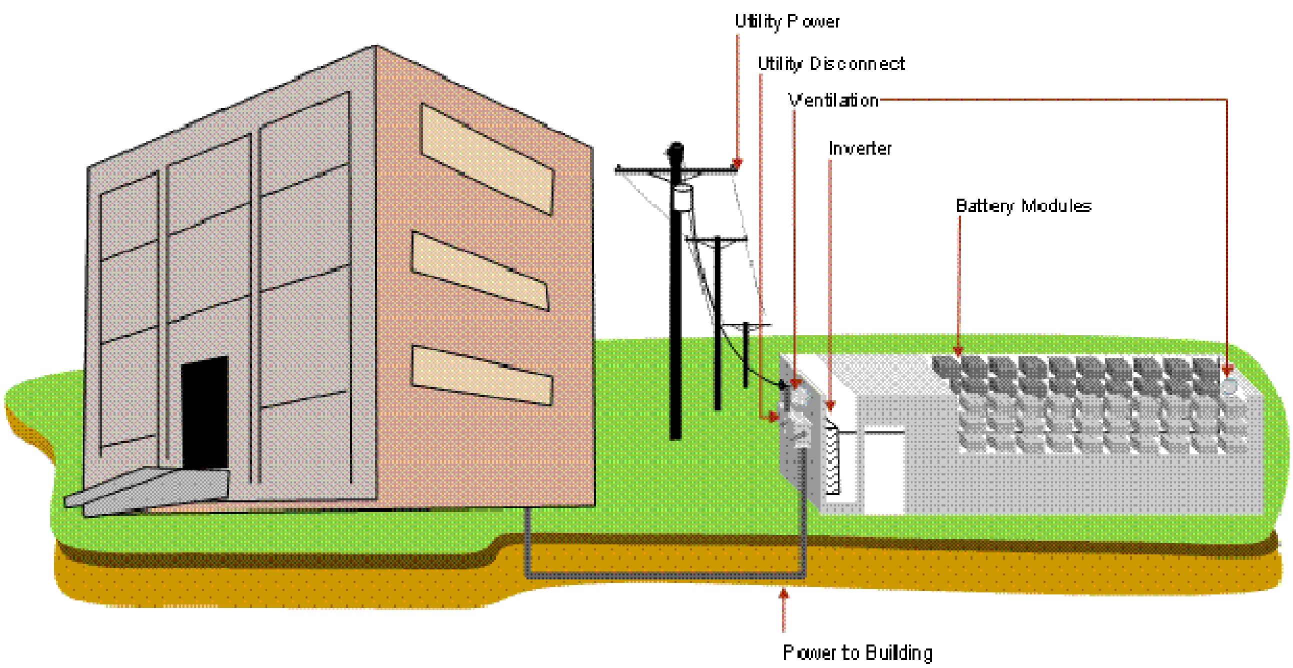
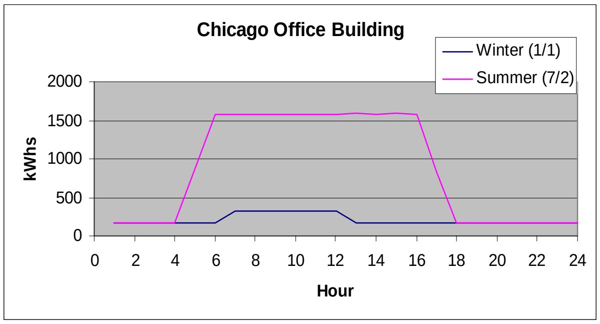


Figure 2-1
Typical Distributed Storage Architecture



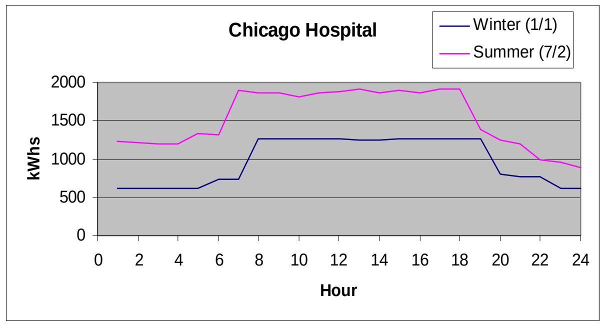


Figure 2-2
Example Commercial-Building Hourly Load Profiles

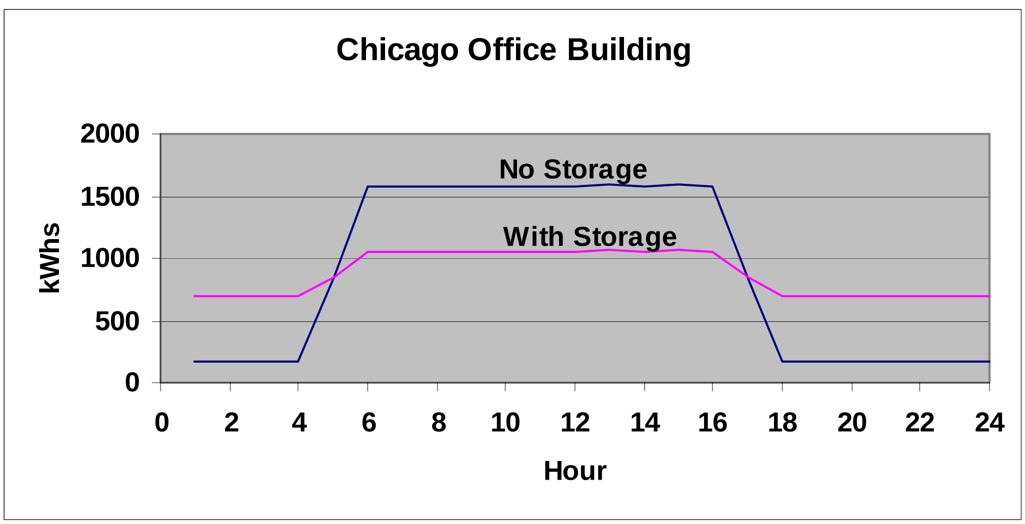


Figure 2-3
Illustrative Distributed Storage Operational Strategy

The economics of such a system from the user perspective would be determined by:

- The cost and performance characteristics of the energy storage system; and
- The utility rate structures—particularly the difference between nighttime and daytime prices.
- End-user bill savings and pay back requirements.

In this model the user benefit is reduced energy costs due to the difference in nighttime and daytime prices (including the effects of demand charges). There are other benefits that would be associated with the use of such systems:

- Enhanced power quality and reliability for the end user (the basis of most current sales of battery systems for emergency power); and
- More efficient use of generation and T&D assets of the electric utilities. If put into widespread use such DES systems would have the double benefit for utilities of increasing power sales and decreasing overall infrastructure costs.

These other benefits are not formally considered in the following example economic analyses.

The following simplified high level analysis is intended to indicate the impacts of key storage system cost/performance characteristics on system economics[1]. We project the cost of electricity (COE) delivered by the storage system as a function of:

- Storage System Characteristics:
  - Round-trip efficiency
  - Capital costs
  - System life (number of cycles); and
- Utility Rate Structure Characteristics (simplified to show typical daytime and nighttime electric prices).

We neglected maintenance costs during the normal life of the storage system and performance degradation as the system ages.

The COE as delivered by the storage system (which includes the cost of electricity purchased at night to charge the storage system) is then compared to the example daytime electricity prices (taking into account the impact of demand charges).

The analysis was undertaken over a range of utility rate structures and storage cost/performance characteristics consistent with the state of the relevant industries in 2005. Of particular importance in determining economics are the differences between daytime and nighttime electricity prices—some of which are indicated in Figure 2-4. These indicate that:

- The price of off-peak electricity ranges from $0.02/kWh to $0.13/kWh, depending on city;
- The price of peak electricity ranges from $0.09/kWh to $0.39/kWh.

These energy prices include the average impacts of demand charges. Separating demand-charge impacts from energy-cost impacts would require detailed economic analyses performed on an hour-by-hour basis using load profiles specific to the building type of interest.

[1] In 2006 EPRI will publish a more comprehensive assessment of the market, costs, and benefits for distributed energy storage from both the end-user and utility perspective. This report is titled: Market Driven Electric Storage Systems: Requirements for Utility Industry Load Management Applications.

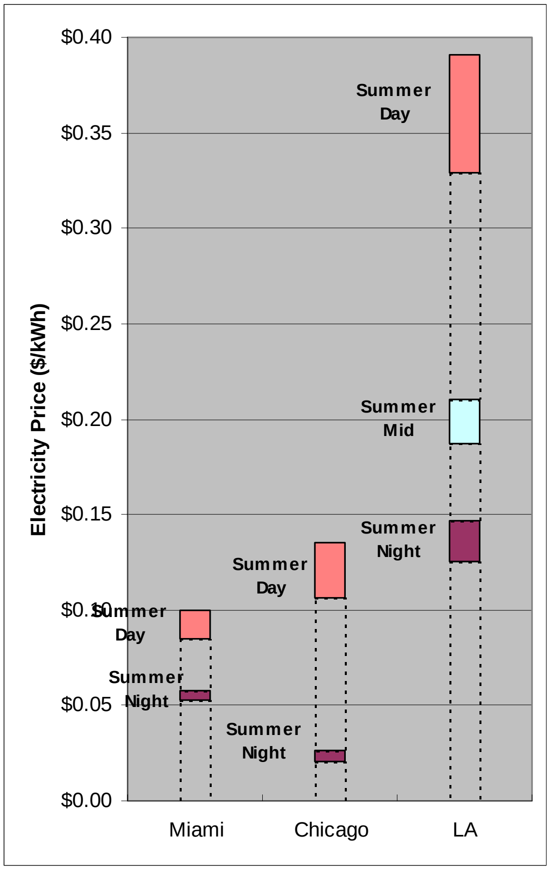


Figure 2-4
Example Electricity Prices Applicable to Large Commercial Buildings

Key estimates and assumptions used in this economic analysis are:

- System life is governed by number of charge/discharge cycles;
- One charge/discharge cycle/day, 268 days/year, corresponding to a cycle life of 1340 for a five-year life and 2680 for a ten-year life;
- Round-trip (charge/discharge) efficiencies ranging from 75% to 95%;
- 75% of the nominal battery storage capacity can be used (consistent with long cycle life and allowing some contingency for uncertainties in state-of-charge measurements);
- Electricity used for night time charging costs $0.05/kWh;
- No maintenance costs;
- No performance degradation over the life of the system;
- Negligible salvage value at the end of system life;
- System installed cost is 2.2 times the OEM battery cost (see discussion below); and
- The total installed cost is paid for by a five-year loan at an annual interest rate of 7%.

The 2.2 mar-up (OEM battery cost to system installed cost) is based on:

- An assessment (Zogg) conducted for DOE on use of distributed power and energy storage in commercial buildings.
- In this study the 2.2 markup was arrived at by considering a building application with energy storage and power requirements of 5.500 kWh and 275 kW (peak) respectively. An application like this with a high energy to power ratio does not stress the rate capability of the battery.
- In this analysis the battery and power electronic costs were $100/kWh and $50/kW respectively.
- To arrive at the purchase price of the system a .50% markup was applied to the OEM hardware costs for the battery and power electronics.
- The installed cost was then obtained by applying an additional 50% markup over the purchase price of the system.

Based on the above assumptions, the Cost of Electricity (COE) delivered by the energy storage system is calculated with the following:

COE = Nighttime Electricity Purchase Price + (Installed Cost + Interest Payments)/ Cycle Life

In the 5 year battery life case the period of the loan equals the life of the battery, however, in the 10 year life battery, the cost of the 5 year loan is spread out over the life of the battery. In this high level analysis, we do not assign any scrap value to the battery.

The results of the economic analysis (Figure 2-5) indicate that threshold economic performance (i.e., saving money based on the spread between peak and off-peak prices) would require achieving aggressive cost/performance characteristics. However, as indicated subsequently, the required cost/performance characteristics for regions having high daytime electric rates are not more aggressive than those targeted by industry and government for a wide range of vehicle applications. The specific cost/performance targets indicated by the analysis are discussed below.

a) Based on loan over 5 years at 7% interest. Maintenance costs neglected. Performance degradation with time neglected.
b) OEM cost is marked up by 2.2 for total installed cost including power and interconnect electronics, BOP, and installation

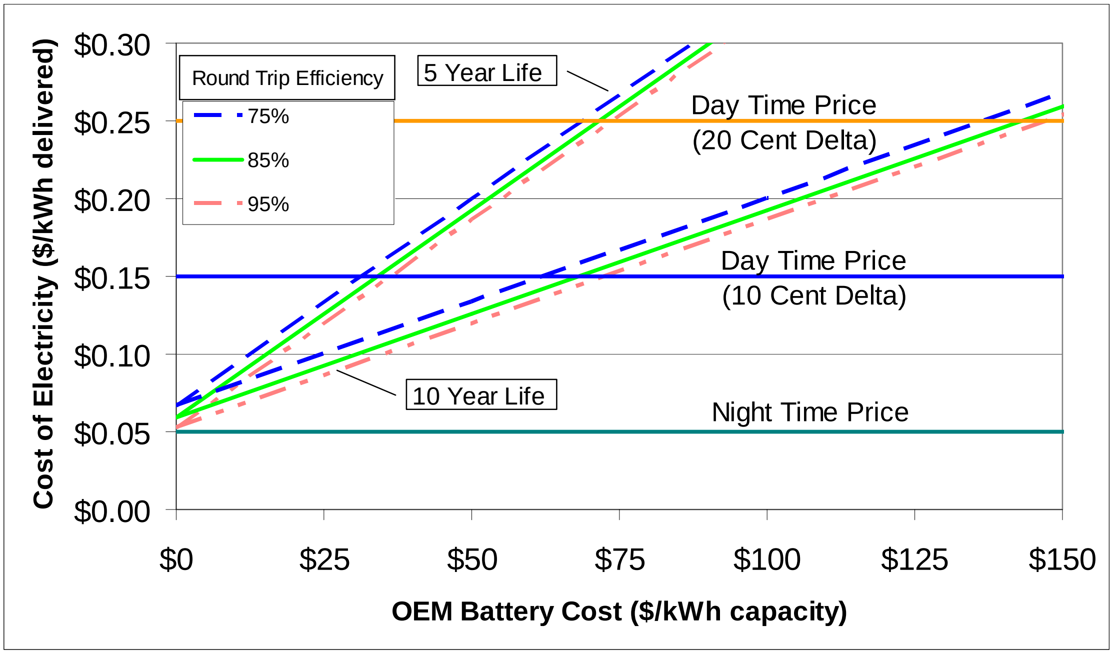


Figure 2-5
Results of Economic Analysis

Key Targets (for competitive economics)

Overview

The cost/performance targets indicated by Figure 2-5 are those needed for high duty cycle applications where the system is utilized on a daily basis for some combination of peak load reduction and energy cost reduction (taking advantage of low nighttime rates). While performing these functions the system will also provide additional levels of power quality and reliability.

Power Electronics - Impact:

The overall energy storage system (Figure 2-1) includes energy storage (battery and battery management system), an enclosure (if environmental control is necessary), and a power electronics package which provide several key functions in interfacing the storage subsystem with the charge and discharge functions compatible with utility supplied power. This assessment focuses on the energy storage subsystem - however, the power electronics subsystem can represent 20% to 30% of system costs based on current technology. These costs are expected to drop significantly as the result of both technological improvements and manufacturing scale driven in large part by the rapidly growing hybrid vehicle market which uses similar electronic elements. Thus, energy storage system economics could also be improved by the developments in mobile power electronics.

The rationale for each of the target parameters for the storage subsystem is discussed in the following sections:

Round Trip Efficiency

The round trip efficiency refers to the ratio of energy delivered to the load to the energy used in the charging process - i.e. a round trip efficiency of 70% implies that only 70 kWh of electricity is provided by the energy storage subsystem for every 100 kWh of electricity used in the charging process. The "lost" energy shows up as resistance (and heat) losses in the storage medium. In emergency standby power applications the round trip efficiency is not (within reason) very important since little energy is used and the user benefit is related primarily to power reliability.

For the range considered, 75% to 95%, and the assumed utility rate structure, round trip efficiency did not have a major impact on economics. The low evening rates were a significant factor in this outcome.

Capital Costs

For regions of the country having high nighttime to daytime rate differentials ($0.20/kWh or more), analyses by TIAX and others indicate the allowable capital cost range is $150/kWh to $300/kWh for the installed system with the upper end of the range assuming high daytime electric rates and that a premium is allowed to reflect the power quality/reliability functions on site storage. The allowable capital cost is also contingent on achieving the life/c goals (10 years +) discussed in the next section. With this capital cost range the cost of power associated with capital alone (i.e. free energy) is in the range of $0.04/kWh to $0.08/kWh.

The cost of a battery technology contains the following contributors:

- At the cell level the electrodes (anode and cathode active materials), the electrolyte (solvent and salts), electrode substrates and current collectors will be the major components. The types and amounts of materials will influence the cost contribution of each component. The electrode materials will be the largest mass of material and most expensive. At high production volumes, materials should be the dominant cost contributor. Additional components include cell packaging (can, cover, seal, vent, and terminals) and possibly safety devices.
- At the module level, cell interconnects, electronics components (active and passive) for safety, cell balancing, and monitoring, thermal management, and packaging will add to the cell cost. At the module level, thermal management may include air or liquid cooling and the packaging to uniformly provide cooling or heating to all cells. The module may also contain a battery management system depending on the control philosophy (distributed or centralized).
- At the battery level, the modules will require interconnects, additional electronic components for safety, control, and monitoring. The central sources to provide heat and cooling would also come in at this level.

- At the system level power electronics and controls for interfacing with the building and grid would add to the overall cost. Communication capabilities to centralized monitoring facilities could also be included at this level particularly at the prototype stage of development.

Life/Cycle Characteristics

The useful life of batteries is tightly tied to how the charge/discharge cycles are controlled and the absolute levels of charge and discharge utilized. For example, high discharge levels (80%+) result in smaller, less costly, battery systems but at the expense of reduced cycle life.

In the types of applications assumed in this analysis the battery systems will go through one cycle per business day whereby it is charged at night (over a roughly 8 hour period) and discharged during the day as appropriate to maximize energy/demand charge savings. Even with the aggressive capital cost targets of section 2.2.3, the useful life of the battery system will need to be, at least, 10 years which implies approximately 2,600 cycles. For the purposes of this study we sought cycle life data for discharge levels of 80%.

O&M Costs

In general, battery technologies are passive and do not have moving parts which are the major source of routine O&M in engines and other power conversion technologies. However, some battery chemistries, such as flooded lead acid and nickel cadmium, may evolve gases (hydrogen) during their operation or have and require some form of periodic maintenance to ensure their reliability and life. Flow batteries involving balance of plant components to circulate will require periodic maintenance for this rotating equipment and components related to control of the system. Some battery chemistries are also sensitive to environmental conditions (temperature, etc) which may require maintenance of their enclosures (fans, etc). The issue of O&M is considered quite important by the user community as exemplified by their feedback to the companies now providing backup power supplies based on battery technologies. Batteries with sealed designs and broader temperature operating ranges were ranked higher in this assessment.

Safety/Environmental Characteristics

The safety data from manufacturers and standards organizations and TIAX safety data were considered in this assessment. Any battery technology can fail, however, through testing, field experience, and modeling batteries have been engineered to balance performance and safety for each application. Additionally protocols can be defined for each battery chemistry that maintain the battery within a safe operating window. Aqueous based batteries are inherently safer than non-aqueous because of the lower energy content of the electrode and electrolyte materials, however, even these chemistries under abuse conditions may generate hydrogen which can explode. Recombination catalysts, cell designs that allow gas to move through the cell, vents, and cell monitors have been developed to avoid these conditions. Non-aqueous battery chemistries contain more energetic electrode materials, i.e., lithium or sodium, and organic electrolytes that can behave like a fuel. Consequently, more sophisticated battery controls and monitors are used with these chemistries. Recognizing these issues lithium ion developers are developing inherently safer electrode materials, cell designs, monitoring methods, and operating protocols. Yet with all of these precautions, battery failures can still occur because of manufacturing defects that become evident after some period of use. For newer larger cell designs in large batteries, extensive testing under field conditions may be required to demonstrate safe operation.

Disposal issues are determined by the materials/chemicals of the battery chemistry. Unlike the safety question, some of the advanced battery technologies, i.e., lithium ion, may be friendlier to the environment. The aqueous chemistries contain lead, cadmium, and nickel all of which have significant limitations on release rates. Lithium batteries may also contain nickel and cobalt, however these may be replaced with greener materials such as iron and manganese. Due to the large size of BES batteries, whatever the chemistry, recycling programs can be instituted to address environmental concerns.

Company and Technology Characteristics for Commercialization

Development Status:

The development of new battery chemistries is a long process. Primary attention in this study will be given to those which are sufficiently advanced in the development process that they might be available for stationary applications in a 5 to 7 year time frame - at least for initial evaluation purposes. An additional consideration is that it is very difficult to assess R&D efforts which are not at this stage of development. This may be an area of future work.

HEV Linkages:

There are major incentives for battery developers/manufacturers to increasingly focus resources on HEV applications given the projected rapid increase in this premium priced market. Most of the battery architectures developed initially for portable power markets are now or are expected to be also utilized in HEV applications (nickel metal hydride in the Prius and lithium-ion under development) leading to large efforts to increase the scale of the cells used in these technologies to levels of interest to stationary applications. If the technologies being pursued for HEV applications can meet stationary requirements there would be a strong industrial base for manufacturing and technology refinement driven, in large part, by HEV applications. Economies of scale in raw materials production, cell production, and battery electronics are critical to cost reduction.

Major Company Support:

The development of battery technology to the point of commercialization is a long and costly process particularly given the increasing attention being given to safety and environmental issues. Those developments being pursued by major companies with large resources are, therefore, most likely to meet the criteria of being able to bring a promising technology to the point of commercialization in a 5 to 7 year time frame. Also, many promising battery technologies having applications in the large portable power and, recently, HEV markets are purchased by major companies even if initially developed by small companies and/or academic organizations. As a result, no major battery development has been commercialized by a "small" company over the last 20 years. For example, commercialization of Li-ion technology in the early years was driven by Sony.

Stationary Focus:

There are a few battery developments which are focused on stationary applications and are not applicable for the light duty HEV or portable power applications which are driving most battery developments. These include high temperature batteries (sodium sulfur and sodium nickel chloride) and flow batteries. As indicated subsequently, several of these have been used in stationary applications as part of demonstration projects usually with utility support. As such, the utility industry is up to date on these technology options and they will, therefore, not be discussed in detail in this report so that more attention can be given to technology options showing potential for large improvements.

Generally desirable characteristics of a technology developer would include:

- Prior experience in developing, engineering, and demonstrating new applications, particularly with larger cell sizes
- An understanding of safety issues in large battery systems and the experience in designing in safety
- An established support organization to address issues in prototype field systems
- A stable organization with the potential to provide support over the 5 to 10 year life required of these systems
- Manufacturing capabilities to produce large numbers of cells, large cell sizes, and the quality control procedures and culture to procure or produce consistent materials and cells.
- Experience in designing and manufacturing cost effective systems
- Financial resources to invest in an emerging market and manage the potential liabilities

3
OVERVIEW OF BATTERY MARKETS TODAY

Battery Types

Table 3-1 provides an overview of the battery technologies that will be considered in this assessment. Additional information on basic battery chemistries, cell types, and cell constructions can be found in battery handbooks, for example The Handbook of Batteries edited by David Linden and Thomas Reddy. Life, cost, and competitive intensity were selected as the most relevant metrics for this snapshot. Life and cost are critical to the economic viability while competitive intensity addresses market forces relative to cost reduction and technology innovation. Competitive intensity includes factors such as the number of companies offering products, alternative technologies, and the market pull for premium performance. A last column highlights the strengths and weaknesses of each technology. A number of the technologies are not fully commercialized at this time, including sodium sulfur (NaS), sodium nickel chloride ($NaNiCl_2$, ZEBRA), and the flow batteries. The projected costs of these technologies are well within the targets, however, high volume production prices have not been demonstrated in actual sales. As such cost is listed as TBD (to be determined). The cost of typical NiMH and Li-ion cells are listed at greater than $650, however prices of commodity Li-ion cells to OEMs have dropped to around $250/kWh.

Rechargeable battery markets can be divided into large and small cell applications. Of the listed types, lead-acid and nickel cadmium are the most mature technologies. On a shear volume basis, overall battery sales are dominated by automotive lead-acid batteries for OEM and replacement car markets for starting lighting and ignition (SLI). Other large cell applications include industrial (electric forklifts and UPSs), telecom un-interruptible power supplies (UPS), railroad, aircraft, and marine applications. Larger cell sizes designed for energy applications with deep discharges typically have flooded designs for both lead-acid and nickel cadmium batteries. Sealed valve regulated lead acid (VRLA) have been used for stationary applications but have significantly less deep cycling capability but require no maintenance.

NaS and ZEBRA are high temperature (e.g., 300^oC) batteries initially developed for electric vehicles. Once the batteries reach their operating temperature normal operation (discharge and charge) will maintain the battery temperature without external heating. Flow batteries have the attributes of both fuel cells and batteries. They consist of a power generation cell and separate storage reservoirs for the liquid anode and cathode reactants. The reservoir volume determines the energy capacity of the battery and the electrode sizes determine the power capability. Nickel metal hydride (NiMH) and Lithium-ion (Li-ion) batteries are used primarily in portable applications. NiMH is the battery now used in HEVs, while HEV Li-ion batteries are currently in development. Table 3-2 summarizes market applications of the battery technologies. The category Industrial/Heavy Duty also includes aerospace and marine batteries. This category is checked for Li-ion because of satellite and prototype batteries for submersible vehicles. We were told that Boeing will use Li-ion batteries on a new airliner.

Table 3-1
Overview of Battery Technology Attributes

Technology	Life	Cost $/kWh[a]	Competitive Intensity	Strengths and Weaknesses
Pb-Acid	5-20 yrs, limited cycles	200-300	High	"Low" cost option for UPS and telecom applications, life sensitive to operating temperatures, limited deep cycle life, mature technology
NiCd	15-20 years Cycles >1000	500 - 600	High	Robust technology, long life, high power for UPS and telecom, high cost, mature technology
NaS	>10 years >2600 cycles	TBD	Low	Single developer, near commercialization, high temperature battery, developed for stationary markets
$NaNiCl_2$ "ZEBRA"	>10 years >2600 cycles	TBD	Low	Single developer, near commercialization, high temperature battery, developed for EVs and HEVs, some stationary prototypes
Flow Batteries	Long life claimed	TBD	Low	Under development since 1980's by small companies for stationary applications
NiMH	10 years 1300 cycles	>650	High	Cycle number from Cobasys for 80% DOD, battery now in HEVs, High cost, temperature sensitive
Li-ion	>10 yrs >2,000 cycles	>650	High	High energy density, high power, can demand premium prices, increasing market share and number of applications

a) Pb-Acid and NiCd estimated OEM battery costs; NiMH and Li-ion costs will vary with performance of the product and the target application, however, current costs are generally much greater than the targets for stationary applications.

Table 3-2
Battery Technology and Market Applications

Battery Technology	Chemistry	Portable	Industrial Heavy Duty	Stationary	HEV
Pb-Ac	Aqueous		√[1]	√	
NiCd	Aqueous	√	√	√	
NaS	High Temperature			√	
ZEBRA	High Temperature			UD	√
Flow	Aqueous			√	
NiMH	Aqueous	√		√	√
Li-Ion	Non-Aqueous	√	√	√[2]	√

UD – under development; [1] also SLI batteries for automotive and trucks; [2] products recently introduced

Several electrochemical storage technologies were not considered in this assessment. Electrochemical or ultracapacitors were not considered in this assessment because their strengths are best suited for pulse or transient power applications related to power quality and UPS with smaller energy requirements than targeted in this assessment. Metal-air batteries were not considered because of the difficulties in recharging these systems and the issues of dealing with carbonation of their alkaline electrolyte. Metal-air batteries, where the anode (metal) is mechanically recharged, have been evaluated for transportation applications; however, they were not considered appropriate for low maintenance stationary applications. Nickel-zinc batteries have been considered as lower cost alternatives to NiMH. Due to the cycle life issues associated with the recharging of the zinc electrode, this technology was not considered for stationary applications.

Portable and HEV Battery Technologies

The explosive growth of digital product markets has triggered over a decade of battery innovation and expansion in production capacity. Development of HEVs and the rapid rise in energy prices may be creating the same market dynamics for large high power cell designs with long life. Portable and HEV markets and the emerging economies of China, Korea, and India are changing the industry dynamics with the appearance of significant new battery developers in China and Korea.

Nickel metal hydride (NiMH) and lithium-ion (Li-ion) battery chemistries which dominate portable and HEV markets have evolved very rapidly over a short time period, starting in the early nineties. Their evolution has been driven by the growth in digital electronics and more recently by the introduction of hybrid vehicles. Small cell rechargeable (portable) market growth has been driven by the growth in portable computers, cell phones, video recorders, handhelds (games, PDAs, music players), and power tools. The data in section 3.3 shows the rapid sales volume increase of batteries into these applications. Due to a combination of greater energy and power density, lithium-ion has come to dominate the small cell market segment.

The emerging HEV market will create a growing demand for larger more powerful batteries. NiMH now dominates the market for hybrids, however, battery and car companies are pursuing lithium-ion to increase energy and power density.

Annual Production Volumes for Small Cells (Portable Markets)

Historical

Market sales of small cell technologies (NiCd, NiMH, and Li-ion), shown in Figure 3-1, provides some indication of how technology preferences may evolve in HEV applications. In the 1980s, NiCd was the only available small cell rechargeable technology available for power tools and portable electronics. However, with the introduction of NiMH in the early nineties, NiMH batteries began to displace NiCd batteries for the new portable digital electronics applications because of higher energy density. Unit sales of NiMH cells rose steadily up to 2000. The performance advantages of NiMH were short lived with the introduction of yet another new cell technology, Li-ion by Sony. In 2002 Li-ion cell unit sales surpassed NiMH and in 2003 exceeded both NiMH and NiCd combined. This rapid growth has been spurred by the desire for longer runtimes and increasing power demands in laptops, cell phones, and consumer electronics.

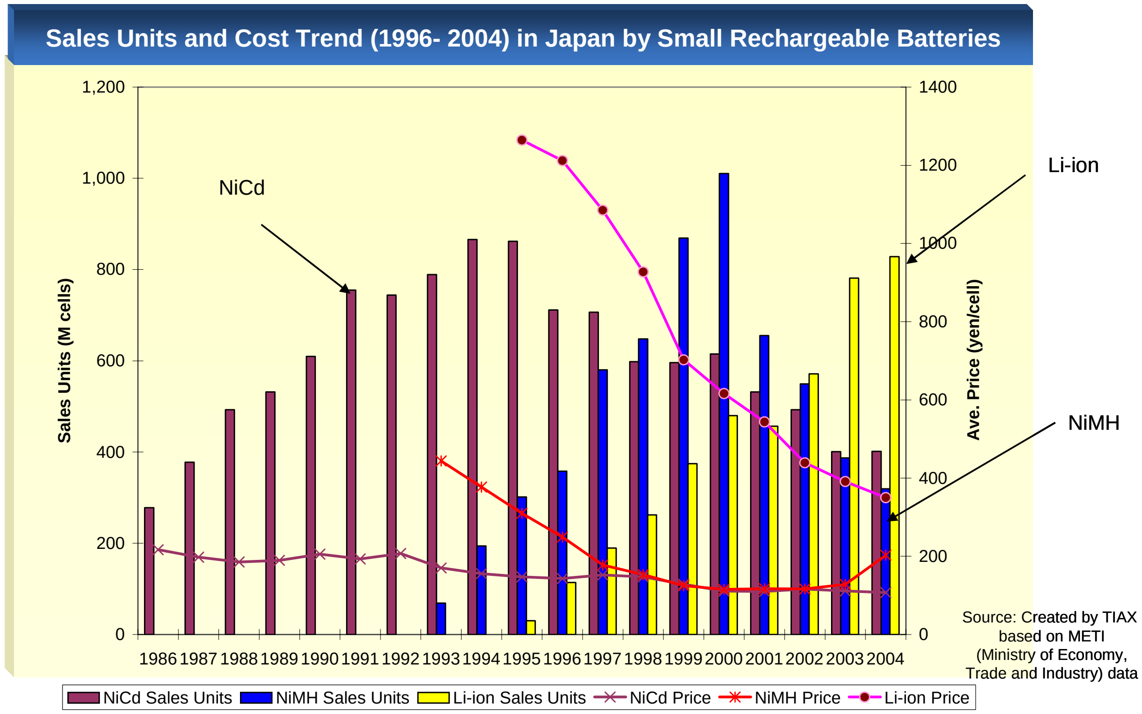


Figure 3-1
Growth, Market Split, and Cell Price of Small Rechargeable Batteries

The sales trends of small rechargeable technologies have been driven by the development of new applications, the constant pressure to increase run times while providing more power, and advances in battery performance. In the period of time after all three technologies co-existed, NiCd became the low cost technology with the lowest energy density but remained the preferred technology in applications requiring high power. Li-ion became the high performance (high energy density) premium battery for portable digital products, while NiMH was caught between NiCd and Li-ion with neither the highest energy density nor the lowest cost. However, recent market data show that on a cost per Wh basis, the average cost of Li-ion cells is converging (Figure 3-2) with that of NiCd and NiMH to an average price of around $680/kWh. In the last year, Milwaukee and Bosch have started to offer premium power tools (higher voltage) based on Li-ion, evidence that Li-ion can now meet the needs of all of the portable markets.

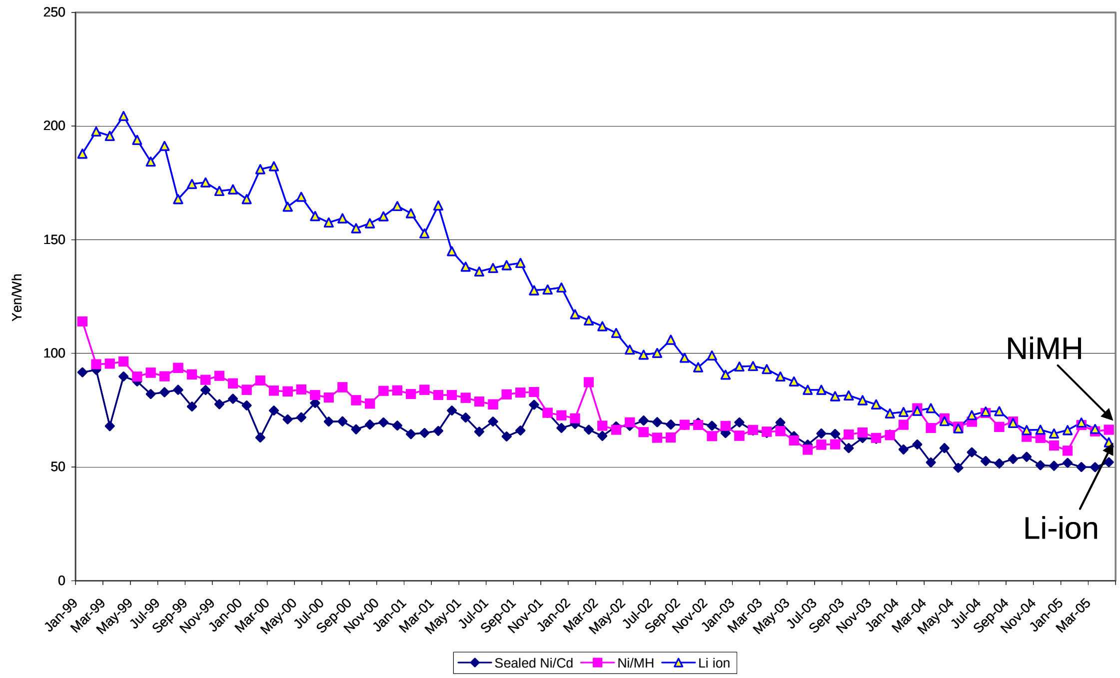


Figure 3-2
Trend (1999- Present) in small rechargeable battery cost, yen/Wh (Source: created by TIAX based on METI data, typical currency conversion of 110 yen to the dollar)

HEV Markets

For the moment, in larger high power HEV cell formats, NiMH dominates the market. As with small rechargeable cells, this dominance may be short-lived because the energy, power, and life characteristics of Li-ion. The OEMs (i.e., Toyota, Nissan, and Fuji) and battery developers (i.e., NEC, Shin-Kobe, Saft, and Johnson Controls) are aggressively pursuing development of Li-ion technologies for hybrids.

Figure 3-3 shows how portable applications for Li-ion batteries are expected to overshadow the HEV battery market for the foreseeable future. The amount of material going into portable markets will continue be large relative to DES markets (e.g., 1 MWh systems). Unit sales of large stationary batteries, on the order of 1,000 units per year, would still be small.

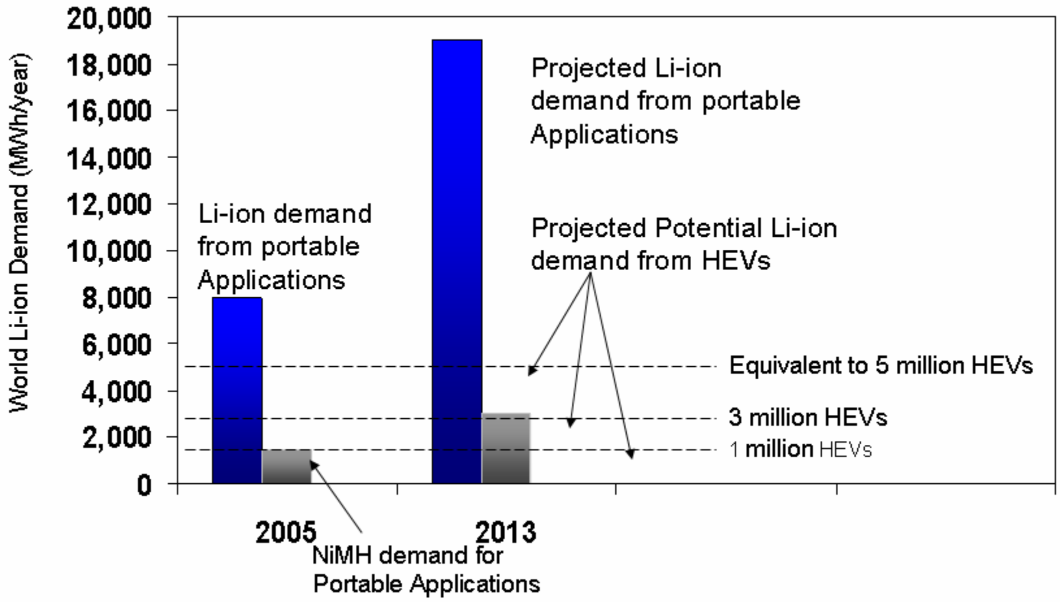


Figure 3-3
Current and projected world-wide demand for Li-ion batteries (MWh/year) (Source: Nikkei Electronics on August 1, 2005)

Manufacturers

In the small cell rechargeable market for portable electronics, the Japanese dominate with Sanyo the current leader. Sony introduced Li-ion technology and dominated the early markets. Sanyo now dominates the market with another five companies forming a second tier. Other countries are now aggressively pursuing the Li-ion market with major manufacturers now established in China (BYD) and Samsung and LG Chem in Korea. A number of startups have appeared in the US with Valence being the most visible to date.

Panasonic EV Energy Co (PEVE) and Sanyo are the major producers of NiMH batteries for HEV applications. Sanyo also supplies NiMH to portable markets. PEVE started as a joint venture of Matshushita Battery Industrial Co (MBI) and Toyota. Cobasys a joint venture of Chevron Corp. and Energy Conversion Devices is the largest potential US supplier of NiMH technology. New releases indicate that Cobasys has “firm contracts” to deliver batteries to automotive companies in 2006. They also offer backup power systems for stationary applications.

Table 3-3
Estimated 2005 Li-ion Battery Market Share by Major Players (total cells: 1.6 billion)*

Country	Company	Percentage
Japan	**Sanyo**	**25**
	Sony	**14**
	MBI**	**10**
	Sanyo-GS	4
	NEC-Tokin	4
	Hitachi Maxell	3
China	**BYD**	**12**
	Lishen	5
Korea	**LG Chem**	**11**
	Samsung SDI	**11**

*Source: IIT presentation at Switching Power Sources and Battery Symposium (April 20, 2005);
** Matsushita Battery Industrial Company

Overview of Stationary Battery Technologies

The utility industry and the DOE have evaluated battery technologies for storage applications for over 20 years. Table 4-1 provides an overview of these technologies with selected demonstrations, mainly to illustrate the size of the systems.

Table 3-4
Selected demonstrations of DES technology

Technology	Rating MW/MWh	Location	Suppliers	$/kWh
Lead-Acid Flooded	20/14	Puerto Rico	C&D/GE New batteries installed recently	200 - 300
Lead-Acid VRLA	4/2.5	Metlakatla, Alaska	GNB/GE	
Nickel Cadmium	46/3.8 (5 min)	Fairbanks, Alaska (GVEA)	Saft/ABB	500 -600
NaS	6/48 1/8	Ohito, CA White Plains, NY[1]	NGK NGK/ABB	250 - 400[3]
Flow Batteries Vanadium Redox	0.25/2	Castle Valley, UT	VRB Sumitomo, VRB ZBB	300 - 650[2]
Zinc Bromine	2/2	PG&E (CA)[1]	Premium Power	

[1] planned for installation 2005/6; [2] VRB web-site; projected cost [3] Projected cost from NGK web-site

Lead Acid

Lower cost lead-acid batteries are used in applications with limited cycle requirements and require controlled environments to obtain maximum life. Operational life of 5, 10, and 20 years are quoted but achievement of these depend on control of many factors including temperature, voltage, depth-of-discharge, and number of cycles.

Nickel Cadmium

Higher cost nickel cadmium batteries find use in high power applications with temperature extremes. The nickel cadmium cell chemistry is abuse tolerant with respect to overcharge, reversal, and standby in any state-of-charge while having long life, i.e. 15-20 years.

The high first cost of nickel cadmium systems is an impediment to wider use while lead-acid will not satisfy the life and cycling requirements of high duty cycle deep discharge energy storage applications.

Sodium Sulfur

NaS continues to be pursued by one consortium (NGK/TEPCO) in Japan. The work started in the early nineties and has been used in numerous demonstrations with approximately 30 MW installed capacity. The most recent demonstration (1MW/8 MWh) is planned for New York State with DOE/NYSERDA support and ABB acting as the system integrator. Since NaS is currently being evaluated by EPRI through several field demonstrations, this report focused only on emerging technologies.

Flow Batteries

Flow batteries have also been around for a long time and are being developed specifically for stationary applications. Several startups have and are trying to commercialize flow batteries. UK based Innogy tried to introduce a sodium bromide/sodium polysulfide based battery. They were unsuccessful and the rights to the Regenesys technology were sold to VRB Power of Vancouver, BC. VRB's main focus has been on the vanadium redox flow battery. The third type of flow battery is based on zinc bromine and several startups, i.e., Premium Power and ZBB, are introducing this technology. ZBB Energy Corp in concert with the California Energy Commission and PG&E will be installing a 2MW/2MWh system on a trailer to provide extra power to substations. The reliability of these systems will largely depend on the MTBF of the pumps, unlike other passive battery systems.

Nickel Metal Hydride

NiMH battery technology has consistently come out second to lithium-ion technology. In portable markets, NiMH has not been able to compete on an energy density basis and it now appears that lithium-ion will also have better power density, as indicated by its introduction into high end power tools. For the moment, NiMH dominates the HEV market but major OEMs have announced plans to introduce lithium-ion batteries in the next few years for both increased energy and power density.

For high duty cycle deep discharge energy applications, NiMH technology may not have the required cycle life for DES applications. SAFT reports their NiMH shows stable life beyond 2000 cycles with 80% depth of discharge. Cobasys on their web site indicate their cells will provide 1300 cycles at 80% depth-of-discharge, whereas 2600 cycles would be required for DES applications. They do not provide calendar life data for the same product. One would expect NiMH technology to have at least 10 year calendar life based on life claims for PANEV cells in the Prius. These cells have cycle lives in the hundreds of thousands but discharge is limited to a narrow window of depth-of-discharge (DOD) around an intermediate state-of-charge. This is very different than a deep discharge DES battery application. However, in discussions with SAFT, they have identified a market niche for NiMH and offer a UPS system based on 100 Ah NiMH cells for float charge applications with a limited numbers of deep cycles.

NiMH has lower potential for cost reduction due to the high content of relatively expensive metals, such as nickel, Misch metal (hydrogen storage materials), and cobalt. In that regard, prices may not have the potential to fall much below $300/kWh.

Leading Japanese companies dominate the NiMH market and may continue to innovate and improve this technology. Panasonic and Sanyo are the major Japanese companies pursuing HEV applications for NiMH with products in Toyota, Honda, and Ford cars. VARTA, now a Johnson Controls company, also has developed HEV batteries. Cobasys, in the US, has made public announcements that they will supply batteries to automakers in 2006. The technology may also advance from research being done on hydrogen storage materials for fuel cell vehicles.

Several smaller companies have emerged with novel designs. Electro Energy in Connecticut is pursuing development of a bipolar NiMH design and has received funding from the Air Force to develop an alternative to nickel cadmium aircraft batteries. They project costs of $250-300 /kWh based on reduction of costly nickel foam current collectors and the reduction of packaging materials enabled by the bipolar design. The bipolar design would still face the inherent life issues of single cell cylindrical and prismatic designs.

Therefore, based on this assessment, advanced developments in NiMH technology should be monitored and followed.

4
CANDIDATE DES BATTERY TECHNOLOGIES

Candidate Technologies

Future emphasis for DES batteries should be in advanced nickel metal hydride, advanced lithium ion and ZEBRA technologies now in-use or under development for HEV applications. Tremendous growth in portable digital electronics and more recently the introduction of HEVs has led to continuing advancements in both NiMH and lithium-ion (LIB) batteries. Additional interest in electric vehicle, aerospace, and military applications of lithium-ion batteries has led to development of large format cells.

ZEBRA, being commercialized by MES-DEA Sa of Switzerland, will also be discussed since it has not received much attention as a candidate for DES applications, yet may have advantages over sodium sulfur. Most of the development effort in ZEBRA has been directed toward electric vehicles, first EVs and now HEVs.

Lithium Ion

Today, Li-ion technology is the premium battery chemistry with the highest energy density. Portable applications have focused on increasing the energy density of Li-ion technology while development of HEV batteries has led to advances in power density, life, and cost reduction.

Li-ion has also gotten adverse attention due to recent safety incidents in consumer devices involving the baseline cobalt-based cathode materials. To ensure the safety of cells, developers use safety devices in the cell, in the battery pack, and include battery management systems (BMS) to monitor and control charging of the battery. They are also working to develop inherently safer cell materials in addition to improved battery management systems.

Baseline Technology

Graphite anode and lithium cobalt oxide cathode materials have been the electrode couple on which the portable market has been built. The capacity of the standard computer cell (18650) has more than doubled since its introduction in the early 1990’s from around 1 Ah to 2.6 Ah today through advances in materials, cell design, and manufacturing processes. This combination of materials has also provided satisfactory life for consumer applications where products typically are used for three years or less. Lithium rechargeable cells may use several electrolytes including liquid, gel, or polymer. Liquid electrolytes are solutions of a lithium salt in an organic solvent. In gel electrolytes (sometimes called gel polymer electrolytes) a salt and a solvent are mixed with a polymer to significantly increase the viscosity. Polymer electrolytes are solvent-free systems with a conductive salt dissolved into or bonded to the polymer. Polymer electrolytes have lower conductivity and are generally not used.

Cells are available in cans (cylindrical or prismatic) and in laminate packages. The term lithium ion is usually associated with liquid electrolyte cells in cans, while polymer lithium-ion commonly refers to laminated foil cells with gel electrolytes and bonded electrodes. The laminate batteries are used in applications where a thin, high aspect-ratio form factor is desired. Stationary batteries would probably be made up of large ampere hour cylindrical cells with liquid electrolytes.

Another material option for the anode is lithium metal, however, one company, Avestor in Canada, has tried to commercialize this technology for transportation and stationary applications. Recently the transportation program was stopped, while they continue to offer products for power backup applications. The deep cycling characteristics of the lithium metal anode are not as good as the intercalated carbon materials.

New Li-ion Technologies

Battery companies are developing new materials to meet the performance, life, safety, and cost requirements of EV and HEV applications. These developments will also potentially benefit stationary applications. One area of focus that has been critical to increasing power, energy density, and safety has been new cathode materials as summarized in Table 4-1. Several companies have already introduced commercial products for stationary and telecom based on these new cathode chemistries.

Saft, a major battery company, is a proponent of nickel oxide cathode systems and is developing this technology for both HEV and stationary applications. The Intensium Flex product line for stationary applications has a projected life of 20 years and cycle life of 3000 cycles (80% DOD) at 20^{o}C and greater than 10 years at 40^{o}C. This product line comes in three designs optimized for energy, power, and a balance of energy and power.

Valence, a startup company, has introduced phosphate based products for stationary and transportation applications. Their K-Charge product line has a rated cycle life of 2000 cycles at 80% DOD (23^{o}C) and a calendar life on float of 20 years at 20^{o}C to 60% of original capacity. Valence is now pricing their products at around $600/kWh.

Both of these technologies are targeted to displace lead-acid batteries in UPS and telecom applications. The product brochures emphasize long cycle and calendar life and wide range of operating temperatures, -25 to 60^{o}C. At this time, these products are priced on the premium end.

Several Japanese companies are pursuing the manganese oxide path (e.g., Shin Kobe and NEC Lamillon) in conjunction with several car companies for HEV applications.

Table 4-1
New Lithium Ion Cathode Materials for HEV and Stationary Applications

Cathode	Performance Attributes	Life	Cost
Nickelates LiNiCoAl oxide	Highest Energy Density available	10 - 20 yr life projected by SAFT with 3000 cycles	Driven by Ni prices
Iron Phosphate	Lower Power and energy density	Long life projected (10 yr with deep discharge)	Low cost material
Manganese	High Power	Solubility issues at partial SOC and high temperature	Lowest cost material

EPRI's time scale of 5-7 years for BES commercialization requires that companies need to be working on large scale cell designs now. The literature provides encouragement that developers are working through the design and engineering issues associated with large cells and stationary applications. The SAFT and Valence batteries mentioned above range from 40 to 100 Ah. Data from Yardney and GS-Yuasa provide further indications that battery companies are developing very large capacity (100Ah) Li-ion cell designs. HEV applications typically use 5-10 Ah cell designs.

Lithion Inc (Yardney Technical Products), who developed and supplied the Mars Lander lithium batteries, has delivered a 150V, 86 kWh prototype battery (shown in Figure 4-1) complete with control electronics to the U.S. Navy for a submersible vessel. The complete ship battery will be 300V and 1.2 MWh.

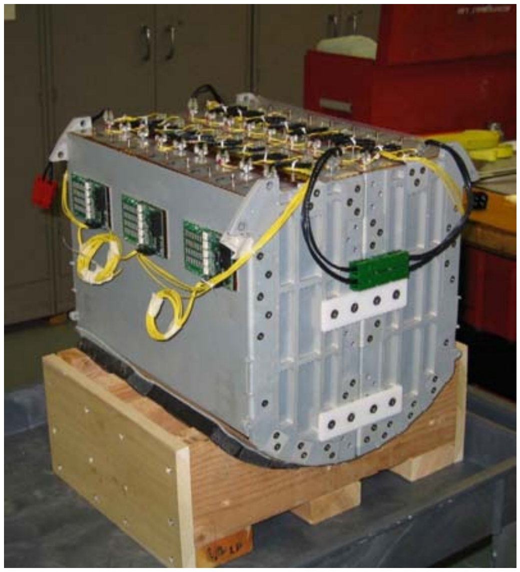


Figure 4-1
Lition 86 kWh Prototype Module

GS Yuasa has presented papers on 100 Ah lithium cells for space (satellite) applications. The GS Yuasa and Yardney batteries are not currently produced at high volumes but demonstrate that large capacity cell designs have been developed and tested sufficiently to place in products.

Li-ion Cost

Intense competition between the major Japanese battery companies and pressure from Chinese and Korea companies to gain market share has been putting downward pressure on the price of Li-ion cells. The recent price of $2/cell for the benchmark 18650 cell (laptop computer cell) with cobalt oxide cathode material corresponds to approximately a price of $250/kWh. A cell includes the active materials, can, and safety devices within the cell. Premium cells with the highest energy density and small form factors will be greater than $600/kWh.

Relative to cobalt oxide based cells, we have estimated the materials cost of the new cathode systems could be significantly lower, i.e., approximately 30% lower as shown in Figure 4-2. These costs, based on materials alone, must be adjusted upward to account for manufacturing costs and corporate markups to project an OEM cell and battery price. In high volume production of material intensive products we have found that materials typically account for 70-80% of the manufacturing cost. Markups to cover corporate overheads and bringing a product to the customer may lead to a price to the customer of up to double the manufactured cost. On top of the cell price, the cost of battery packaging and controls must be accounted for. Summing up all of these contributions results in an OEM battery price projection of about $175- to 250 /kWh for the new chemistries. This projection is aggressive relative to current pricing of premium lithium products, however, might be realized in high volume standardized products.

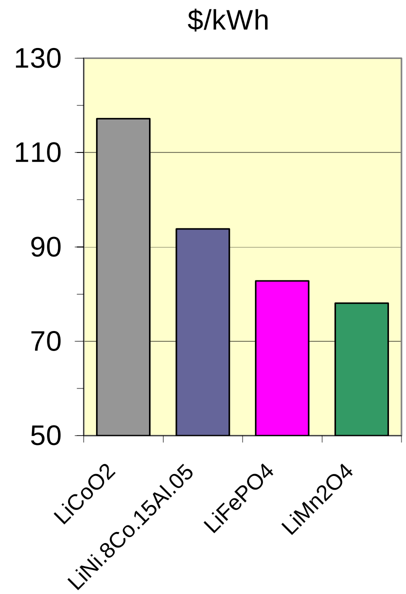


Figure 4-2
Material Cost Projection for Li-ion Cells Based on New Cathode Materials Relative to the $LiCoO_2$ Benchmark

ZEBRA Battery Technology

History

The ZEBRA battery technology was developed by AABG, a joint venture between Daimler and the South African Anglo American Corporation. The technology was sold to MES-DEA of Switzerland after the merger of Daimler and Chrysler. MES-DEA, a supplier of automotive components, has built a manufacturing plant and focused on introduction of this technology into transportation applications including pure electric vehicles and hybrid heavy duty vehicles and vans.

Battery Description

ZEBRA or sodium nickel chloride ($NaNiCl_2$) batteries operate at high temperature (270^{o}C to 350^{o}C) and have a ceramic electrolyte like NaS batteries. Attractive features include: 100% coulombic (Ah) efficiency; and if the electrolyte tube cracks, the cell fails in a safe manner with an electronic short formed between the terminals. Consequently, a large string of cells can continue to operate when a cell fails with only a small diminution in voltage. This attribute makes the ZEBRA cell inherently safer than NaS and batteries tolerant of individual cell failures.

This technology has both high calendar and cycle life with values in excess of 10 years and 3,000 cycles as illustrated in Figures 4-3 and 4-4. Batteries show less than 20% resistance degradation (80%DOD) at 3500 cycles with 100% retention of coulombic capacity as shown in Figure 4-4.

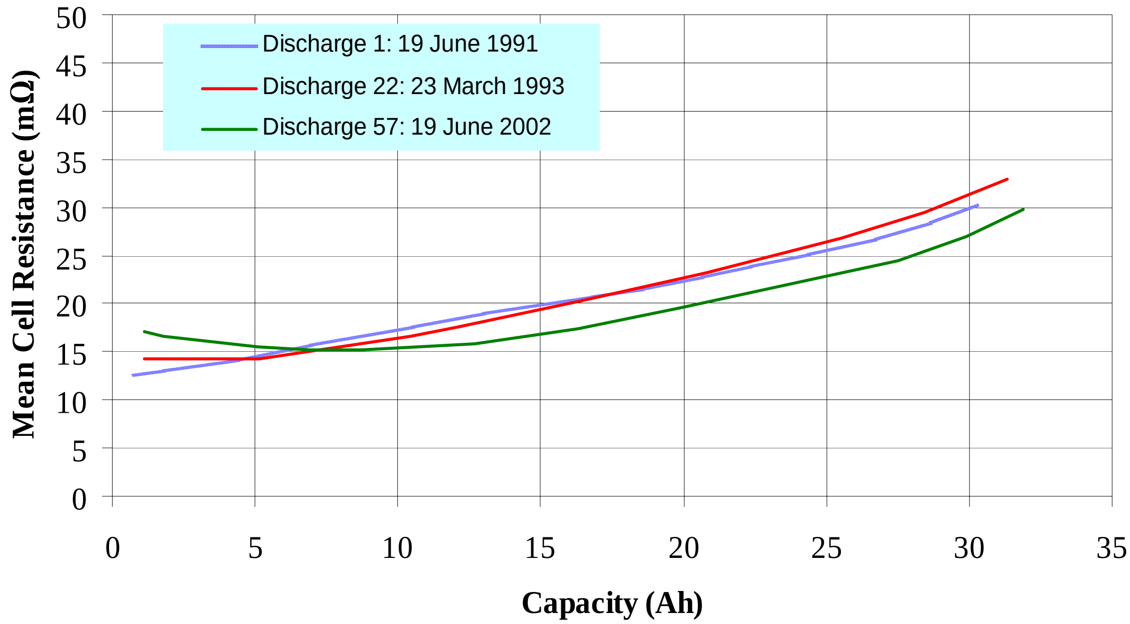


Figure 4-3
ZEBRA SM3 battery exhibited no cell failures and stable impedance over eleven years and 8 complete thermal cycles.

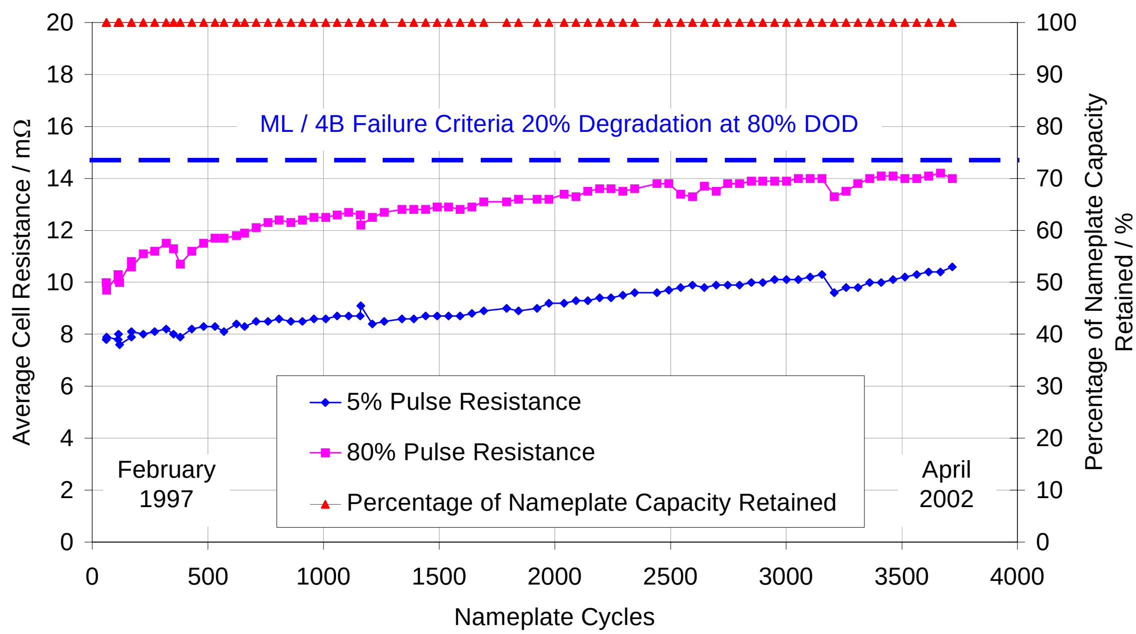


Figure 4-4
ZEBRA batteries exhibit long cycle life (Source: MES-DEA)

Note: the data provided by ZEBRA shows long cycle life, however a more in-depth review of the technology would involve understanding the details of these results and assessing the operating experience from demonstration programs.

Application and Cost

The development of ZEBRA has been primarily directed toward electric vehicles with demonstrations in cars, vans, and buses. The current standard design is a 38 Ah cell which delivers approximately 100 Wh (2.58 V).

The current cost of batteries is around $400/kWh, however, projected selling price (by the developer) of batteries at high volumes are claimed to be as low as $110/kWh. The battery materials, with the exception of its nickel content, are inexpensive and not subject to price fluctuations. Table 4-3, shows the developer cost projection (EVS 20). The high temperature of operation and insulated battery case make the technology tolerant to a wide range of ambient conditions. Consequently, the additional cost of temperature controlled enclosures is avoided. The combination of 100% coulombic efficiency and failing in a shorted condition simplify battery management circuitry.

Table 4-2
MES-DEA Projection of ZEBRA Cost

Part		$/kWh
Cells	Material 70%Assembly 30%Energy	28.3 12.1 1.7
Case	Material 50% Assembly 50%	9.4 9.4
Controller		11.8
Total Cost		72.6
Price	150% of cost	109

MES-DEA has started development of ZEBRA for stationary applications (Dustmann, 2003) with development of increased capacity cells for photovoltaic and telecommunication demonstrations. Additionally, high voltage applications may be possible since cells fail in a shorted state increasing the reliability of large series strings of cells.

Competitive Intensity

MES, the parent company of MES-DEA, is a manufacturer of motors, actuators, and other electrical components to automotive OEMs. The ZEBRA technology investment was made as part of an overall effort to enter into electric vehicle markets. The company understands high volume low cost automotive markets, however, in the battery area has not faced the same competitive intensity as small cell rechargeable manufacturers. However, targeting heavy duty hybrid markets still sets performance, life, and cost targets that are consistent with the requirements of stationary markets.

MES-DEA provided a list of companies evaluating the ZEBRA technology and the number of batteries purchased (Table 4-3).

Table 4-3
List of ZEBRA references back to 1999

Customer	Country	Battery Type	Application	Year							
Customer	Country	Battery Type	Application	1999	2000	2001	2002	2003	2004	2005	*Total*
ABB	Sweden	Z48							4		4
AC Propulsion	USA	Z36	Van					2			2
Aixam Mega	France	Z50								1	1
Altra	Italy	Z5	EV-bus/FC-bus				8	4	0		12
A.T.C. Bologna	Italy	Z5	HEV-bus/EV-bus						21	14	35
Autodromo Modena	Italy	Z5	HEV-bus/EV-bus	23	65	32	65	15			200
BETA	UK	Z5/Z37/Z43						3	5	14	22
BET Services	Canada	Z5	HEV-bus		3			6			9
BredaMenariniBus	Italy	Z5	HEV-bus				6	33	18	1	58
Brusa/Coaster	CH/A	Z37	Special					2	0		2
DaimlerChrysler	Germany	Z5/Z12	Van/Car		18		1	4	0		23
Delta Motors	USA	Z56	Car							3	3
Diesse/Ecolori	Italy	Z39/Z44	Twingo/Smart						6	25	31
EDF/Sodetrel	France	Z5	EV-bus						43		43
E-VERMONT	USA	Z35	EV-bus						6		6
Ferrazzano	Italy	Z5								1	1
Fiamm	Italy	ZS3								6	6
Forghieri	Italy	Z5	Car					1	0		1
Frazer Nash	UK	Z23	EV						4	4	8
General Electric	USA	Z5/Z12/Z37	HEV-bus					14	7	6	27
General Electric	CH	ZS3/Z5								4	4
Gruau	France	Z5							4		4
Heuliez	France	Z36							1		1
Institut Lacznosci	PL	ZS2	Telecom						2		2
ISE Corp.	USA	Z5	HEV-bus				9	5	5	9	28
LPD	UK	Z36	EV Van						2		2
LTI	UK	Z5	EV Van						5		5
Mes-Dea EV project	Swiss	Z39/Z44/Z21	Twingo/Smart						4		4
MicroVett	Italy	Z5/Z23/Z33	EV-truck/Van/Car		2	5	2	14	8	30	61
Modec	UK	Z12								26	26
Ramtonic	France	Z49								2	2
Reva	India	Z52							2	1	3
Rolls-Royce	UK	Z5	submarine						22		22
Samson	CH	Z47							2	3	5
SantaBarbara	USA	Z5	EV-bus		7	11	6	1	0	7	32
Sanyo	Japan	Z5							2		2
SCE Modena	Italy	Z5							1		1
Showa	Japan	Z5/Z35/Z37/Z49	EV car					1	18	7	26
Simpa	France	Z35	EV car					1	0		1
Sowind	Italy	ZS2	Solar Poles						1		1
Tecnobus	Italy	Z40	EV-bus					4	0		4
Tepco	Japan	Z5/Z40								2	2
Think Nordic	Norway	Z23	EV-car				7	0	17		24
Toshiba	Japan	Z5/Z33/Z36							3		3
Trambus	Italy	Z40								56	56
Univ. Pontificia Cile	Chile	Z36							1		1

Even though applications are not listed for all customers, batteries going to ABB, Institut Lacznosci, Sowind, TEPCO, and Toshiba may be directed toward stationary applications. In the US, customers including AC Propulsion, Delta Motors, E-Vermont, General Electric, ISE, and Santa Barbara have generally used the batteries in buses or vans. We spoke with a developer of buses and they said the cells have worked as claimed. ZEV, in Italy, is the single largest user with approximately 1900 batteries purchased for EV-vans.

Clearly, however, the level of effort of MES-DEA can not compare with the resources that continue to be deployed in the lithium-ion and NiMH areas, however, the performance and life of ZEBRA speak to the robustness of the technology.

ZEBRA appears to be another “new” option for the utilities to consider and evaluate for demonstration of DES. In a more in-depth look, some of the following questions or tasks might be considered.

- Validation of the long term cost projection for ZEBRA technology
- What would a MWh ZEBRA battery design look like and implications for cost?
- Ability of MES to scale up production and or to find manufacturing partners

5 CONCLUSIONS

Requirements

A high level economic analysis of distributed energy storage applications yielded the following requirements:

- A 10 year life with a cycle life of greater than 2600 cycles is required to have reasonable capital and battery replacement costs – this is from an end-user requirement. From a utility ownership or dispatch perspective, the requirement for cycle life may be less.
- An OEM battery cost of $150-300/kWh is needed to have widespread economic potential. In this analysis the installed cost, which includes the power electronics and installation, is 2.2 times the OEM battery cost.
- The above analysis assumed negligible maintenance costs which implies a sealed battery chemistry.

In addition to these requirements, a battery chemistry that has minimal thermal management requirements is highly desirable to minimize the capital and maintenance cost of an environmental enclosure.

This study also identified company and market attributes that will improve the likelihood of commercialization of technically attractive technologies. Battery technologies coming out of portable or HEV markets have the benefit of:

- Significant economies of scale in the production of raw materials and cell components/materials due to market size
- Competitive intensity to drive technology innovation and cost reduction
- Significant growth in both portable and HEV markets due to expansion of applications and the economic expansion of China and India

From a commercialization perspective, distributed energy storage applications would benefit from companies with the following attributes:

- Prior experience in developing, engineering, and demonstrating new applications, particularly with larger cell sizes and stringent cost targets
- An understanding of safety issues in large battery systems and experience in designing in safety
- An established support organization to address issues in prototype field systems

- A stable organization with the potential to provide support over the 5 to 10 year life that will be required of these systems
- Manufacturing capabilities to produce large numbers of cells, large cell sizes, and the quality control procedures and culture to procure or produce consistent materials and cells.
- Experience in designing and manufacturing cost effective systems
- Financial resources to invest in an emerging market and manage the potential liabilities

Final Conclusions

The following technologies were not considered candidates for energy intensive DES applications for commercial buildings.

- Lead-acid and nickel cadmium chemistries will not satisfy the life and cost requirements of energy intensive DES applications, respectively. These traditional technologies have established market niches in UPS and telecom applications, even though end-users are seeking alternatives to lead-acid batteries because of life and maintenance issues.

NaS and flow batteries may be potential candidates for energy intensive DES applications with the following attributes.

- The market focus of NaS and flow batteries has been limited to stationary applications, consequently they do not benefit from the competitiveness and economies of scale of portable and HEV markets.
- The technologies are being developed by a limited number of companies and in the case of flow batteries, by small organizations.

Of the two technologies, NaS is furthest along the commercialization pathway having gone through extensive development and demonstrations. Flow batteries are less demonstrated and have the potential for higher maintenance costs due to pumps and piping systems. Ongoing and planned demonstrations will provide additional data for the utility industry to assess the technical viability of these technologies.

- NiMH used in portable applications and now dominant in HEV applications. Issues related with life in deep cycling applications and the potential for costs to drop below $300/kWh need further assessment.

Li-ion and ZEBRA are two emerging technologies which may have the potential to enable energy intensive DES applications.

Lithium-Ion

- Li-ion technologies have experienced significant advances in performance driven by the demands of the ever growing portable markets for digital electronics and the emerging HEV market. Li-ion dominates the portable small cell markets and we anticipate will begin to displace NiMH in HEV in the next 3-5 years. Li-ion material developments are increasing the power, energy, life, and safety of cells while reducing cost. Technology advances are also driven by the competitive pressures of major battery developers in Japan and Europe. Emerging companies in Korea and China are also developing technology to become competitive. In the US, Valence is introducing one of the new technologies that might be suited for stationary applications.

- Li-ion utilizes lower cost materials than nickel based batteries and these may lead to costs compatible with the requirements of DES. Li-ion batteries require more electronics and safety devices and the cost of these must be balanced against the lower cost of cell materials.
- SAFT, an established battery company, recently introduced a Li-ion product for stationary applications with a quoted life of 20 years and 3000 deep cycles. Valence, a startup, introduced another product with a rated life of greater than 10 years and 2000 deep cycles.
- Li-ion is a promising emerging technology which should be closely followed, monitored and assessed for candidate energy intensive DES applications.

ZEBRA

ZEBRA has been tested extensively in EVs and HEVs, but is relatively new to stationary applications.

- The life and projected cost of ZEBRA may potentially satisfy the requirements for DES
- The cell failure mode of forming a short between the anodes makes high voltage strings of ZEBRA cells more reliable than other battery technologies. This failure mode also leads to a safer battery than NaS.
- Even though only one developer is pursuing ZEBRA, they have targeted heavy duty HEV markets which will create economies of scale to bring down cost.

Gaps

Neither NiMH, Li-ion or ZEBRA technology have been considered for stationary distributed energy storage applications, consequently, cell and battery designs and the supporting electronics will have to be engineered for cost, reliability, repair, and safety. Overall DES battery designs including enclosures and environmental controls are needed to estimate the installed cost and maintenance requirements and to assess performance and life in DES applications.

Developers and system integrators with an interest in developing DES markets for their technology will have to be identified. For MEA-DES, the DES market represents a large new opportunity and we would expect significant interest. On the other hand, Li-ion developers have portable, HEV, and UPS markets that are willing to pay higher prices than allowed by large scale DES. A business case will have to be developed and presented that benefits both the battery developer and the utilities.

6
REFERENCES

Robert Zogg, Sean Casten, "Preliminary Assessment of Battery Energy Storage and Fuel Cell Systems in Building Applications", Final Report to National Energy Technology Laboratory (DOE), Contract No. GS-23F-8003H (August 2000)

[EPRI 1999] *Assessment of Distributed Resource Technologies*; prepared for the Electric Power Institute; prepared by TIAX LLC (known at the time of the study as Arthur D. Little, Inc.); EPRI Report TR-114180; December 1999.

David Linden, Thomas Reddy, Editors, Handbook of Batteries, Third Edition, McGraw-Hill (2002)

Hideo Takeshita, "Worldside Market Update on NiMH, Li Ion, and Polymer Batteries for Portable Applications and HEVs", The 22nd International Battery Seminar & Exhibit Pre-Seminar Tutorial, March 14, 2005 (Institute of Information Technology, Ltd)

"Proceedings of the First International Symposium on Large Lithium Ion Battery Technology and Application", June 13 – 14, 2005, Honolulu, Hawaii (Produced by Advanced Automotive Batteries)

"Proceeding of the Fifth International Advanced Automotive Battery & Ultracapacitor Conference", June 15 – 17, 2005, Honolulu, Hawaii

Cord-H. Dustmann, Roy C. Galloway, "ZEBRA Battery Material Cost, Availability, and Recycling", EVS-20, Long Beach, CA (November 2003)

Cord-H. Dustmann, "Stationary ZEBRA Battery", Int. Symposium on Power Sources for Stationary and Distributed Power Systems, Munich, Germany (September 2003)

DTI Global Watch Mission Report, "Electrochemical energy storage – a mission to the USA", (November 2004)

EPRI Report on cost Market, costs and benefits of Distributed Energy Storage.

Websites of selected developers

- SAFT, http://www.saftbatteries.com/
- Valence Technology, Inc, http://www.valence.com/

- ElectroEnergy Inc, http://www.electroenergyinc.com/
- NGK, http://www.ngk.co.jp/english/products/power/nas/

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California, and Charlotte, North Carolina, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together…Shaping the Future of Electricity

Printed on recycled paper in the United States of America

1012983

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue, Palo Alto, California 94304-1395 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com