BATTERY ENERGY STORAGE –
COMING SOON TO A STREET CORNER NEAR YOU?

Jim McDowall
Saft America Inc.
North Haven, CT 06473

ABSTRACT

Distributed generation (DG) has been a very popular subject in power engineering circles of late. To utility personnel wrestling with the problems of aging infrastructure, steadily diminishing transmission capacity margins and power reliability concerns, the idea of simply placing small, efficient generators in the grid at the distribution level is highly attractive. This concept is being enabled by recent advances in the generation technologies themselves, and also in the communications and controls required for a utility to manage these resources in its network.

Although DG units can be implemented on a relatively large scale with combustion turbines rated at several megawatts apiece, there is considerable interest in generation on a much smaller scale, most notably in the form of microturbines and fuel cells. Because of their smaller output, these units are typically placed much closer to the consumer, or even on the consumer's premises. This gives rise to a problem, in that such systems are exposed to the full fluctuations of individual loads, rather than experiencing the averaging effect seen by larger generators. Microturbines and fuel cells are not able to respond rapidly to such load steps, and even if they could, it would probably not be economically feasible to do so. This creates a potential for energy storage systems.

An energy storage system (ESS) can augment a DG unit by providing near instantaneous response to load steps and by supplying short peak loads, while the generator provides the average system load at high efficiency. While many of the loads on the ESS are momentary loads that could be provided by other storage devices, such as capacitors or conventional flywheels, it is often desirable for the ESS to provide a block of energy for a black start of the generator. A battery is the most practical storage device to provide this capability. Battery energy storage (BES) also provides increased flexibility in the type of system loads that can be supported, so it is the storage medium of choice for this type of application.

Another form of DG is provided by renewable energy sources, such as solar and wind energy. The intermittent and/or cyclical nature of many renewables presents a strong opportunity for energy storage, particularly with new regulations coming into place that are aimed at increasing the proportion of total generation provided by renewable sources.

This paper discusses the typical loads seen by BES systems in DG applications, particularly with respect to issues of peak power versus battery energy. Other requirements for these systems are discussed, as are the ability of various battery technologies to meet those needs. The comparison of existing battery types includes vented lead-acid, valve-regulated lead-acid and nickel-cadmium. New technologies, such as lithium ion and flow batteries, are also covered.

MICROTURBINES AND FUEL CELLS

Traditional wisdom was that combustion turbines could not be scaled down to smaller sizes without a serious loss of efficiency. However, the use of high-speed, single-shaft designs, air bearings, heat recuperators and simple generators coupled with solid-state electronics has allowed a new generation of gas turbines to be produced, with outputs of less than 300kW and as little as 25kW. Their relatively low output makes microturbines suitable for small businesses or residential developments. At this stage of their development there is a limit to the number of times they can be started and shut down. This makes them suitable for baseload generation, but not as peaking units.

Much R&D work has been performed on fuel cells, particularly related to their potential use in hybrid electric vehicles to replace internal combustion engines. The fuel cell technology that has the highest potential for near-term deployment uses proton exchange membranes (PEM) to combine protons from a hydrogen-rich fuel with oxygen from the air. The resulting reaction produces water and electrical energy, and is basically the reverse of the electrolysis reaction in vented batteries that results in water consumption. Although fuel cells are electrochemical devices, they should not be confused with batteries.

Fuel cells are generators, while batteries are storage devices. There is in fact a gray area between the two that is represented by some of the new flow batteries that will be discussed later in this paper. These so-called regenerative fuel cells have external 'fuel' tanks, but the power-producing reaction can be reversed, just as in secondary batteries.

For electricity delivery, one of the greatest areas of interest in fuel cells is in residential generators. These self-contained units, about the size of a large refrigerator, contain a PEM fuel cell stack with a rated output of 5-10kW. In most cases, the fuel used is LP or natural gas, so the unit must also contain a reformer to generate the hydrogen ions (protons) required for the electrochemical reaction. The other components of the system are an inverter and a battery for peak loads (more on that later).

Microturbines are now in production, albeit not in very large quantities, while residential fuel cell generators are just beginning to be deployed on a developmental basis. Due to the present strains on the electricity delivery infrastructure in the US, however, it is expected that deployment of these two types of generator will accelerate rapidly over the next few years.

NON-COINCIDENT LOADS

When looked at centrally, the load on a utility grid normally follows a smooth and fairly predictable pattern, with no sharp spikes or other step changes. This is illustrated by the left-side illustration in Figure 1, which shows a residential winter peak-day load curve for an electric system in the Northeastern United States[1]. As the viewpoint moves out towards the consumer, however, the picture becomes considerably more variable, as individual loads start to become prominent. The influence of single loads reaches a maximum when looking at a single household, where the full variation can be seen.

This presents problems in the deployment of small DG units like microturbines and fuel cell generators. It is simply not cost effective to size the generator output for the maximum load, since this load may last for less than a second. Even if the installed cost per kilowatt of these DG units were to be drastically reduced over time, there would still be issues of response time and system efficiency. Both microturbines and fuel cells have relatively slow response times to load steps. In the absence of a 'stiff' grid to fill in the 'gap,' some other solution is required. The most obvious one is to size the DG output for the baseload requirement and to augment this with an energy storage device. The ability of various battery types – both existing and under development – to provide this function will be discussed later in this paper.

RENEWABLE ENERGY SYSTEMS

Another potential use of energy storage is in conjunction with renewable energy systems. Such systems can vary hugely in scale, from a small photovoltaic array on a single home to a multi-megawatt wind farm. In the past, the amount of grid-connected renewable generation, relative to overall generation, was extremely small. Therefore, it didn't matter that peak

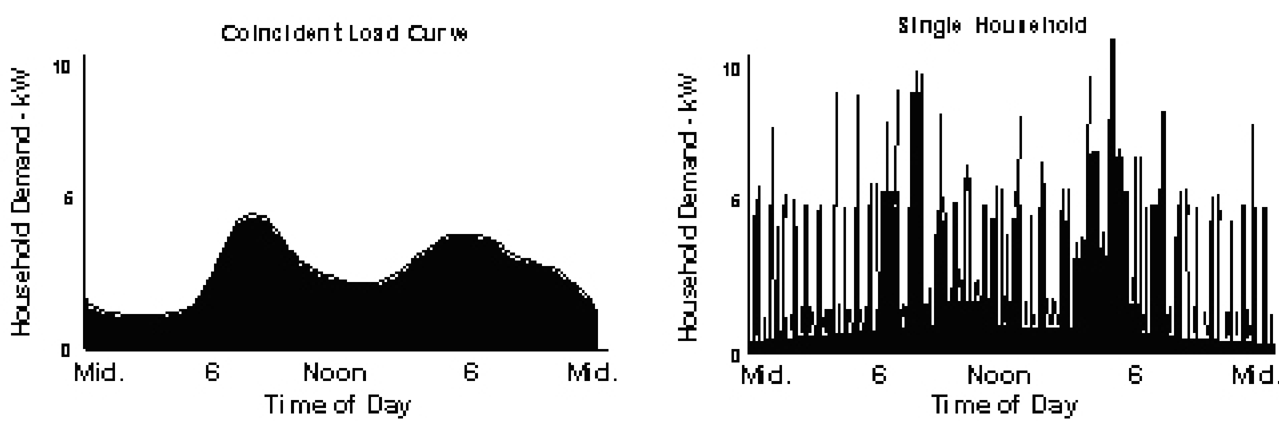

Figure 1 - Coincident and Non-Coincident Loads

generation might not coincide with peak consumption, or that output might be interrupted as the wind dropped or clouds obscured the sun. The utility grid was sufficiently flexible to accommodate these variabilities.

Now, however, grid-connected renewable generation is assuming a much more significant role in many countries, and these issues can no longer be ignored. Under the UK's New Energy Trading Arrangements (NETA), a system of incentives and penalties has been established, with the aim of achieving 10% of national generation from renewable sources by 2010. At the same time, NETA requires planned trades to be implemented at least 3.5 hours before a block of energy is released. For the operator of a wind farm, it simply is not possible to guarantee that the wind will be blowing several hours hence! Quite apart from the trading issues, a sudden loss of generation from a large renewable source would be very disruptive to a utility system.

Energy storage provides two solutions for these problems. It can be implemented as spinning reserve, so that output can be ramped down in a controlled manner, without disrupting the grid. On a larger scale, energy storage can provide a load leveling or commodity storage capability, so that energy can be dispatched when it is needed. Indeed, such a use is not restricted to renewable generation. Ultimately, it can take the form of energy arbitrage, where the stored energy is held back ready for immediate release when the price on the spot market reaches a certain level.

BATTERY REQUIREMENTS

While the battery requirements of the various energy storage applications are hardly unique, they can be quite punishing for today's stationary batteries. Large systems for load leveling or commodity storage operation are subjected to repeated deep discharge cycles, sometimes more than once per day. Smaller systems used to support DG units may be installed in outdoor cabinets subject to environmental extremes, and must repeatedly supply very high power discharge pulses. Table 1 shows the importance of a number of battery requirements, based on operation in DG support or commodity storage applications. It should be noted that this is a generalized view, and that it is foreseen that in many cases, more than one energy storage application will be supported by a single battery system.

To understand this information, it helps to regard commodity storage BES systems as being fixed with respect to a large 'object' in a utility grid. This could be a wind farm, a generating station or the end of a transmission line. Such a system will generally have a capacity of tens, if not hundreds, of megawatt hours, and will require a dedicated structure to house it. Such a structure would be purpose-built, and would therefore provide an environment that is favorable to the battery type in question. Although compact size is desirable, under such circumstances it is less important than a good deep-discharge cycling capability. It is also safe to assume that this system would not need to be moved to another location during its operating life.

DG units, on the other hand, will be implemented on a much smaller scale. They will frequently be located on a customer's premises, where space may be at a premium and the environment may be much less battery-friendly. They may also be used for capacity deferral, meaning that their use will temporarily offset the need for a new distribution feeder, for example. As

Table 1 - Battery Requirements

	DG Support	Commodity Storage
High discharge power	✓	
Deep discharge cycling		✓
Shallow discharge cycling	✓	✓
Operation at temperature extremes	✓	
Compact size	✓	
Transportability	✓	

loads grow and the feeder becomes more economical, it may be constructed and the DG units may be moved to another location. On the cycling side, batteries supporting DG could be discharged very frequently at high power, but those discharges may only last for a second or two and the capacity removed from the battery would be very small. It is for this reason that a deep discharge capability is not seen as a major requirement for batteries in distributed generation applications.

BATTERY TYPES

This section of the paper will briefly discuss the main battery types for use in energy storage applications – both now and in the future.

Lead-Acid Batteries

Despite having been developed as far back as 1860, lead-acid has remained the most popular electrochemical storage medium. This is largely due to the fact that it can be mass-produced at a lower cost than other battery types. The construction of these batteries also lends itself to specialized designs, ranging from automotive batteries to central office telecommunications products. In the last 20 years, valve-regulated lead-acid (VRLA) designs have appeared and have taken over large sections of the overall market. Although not as reliable or as long-lasting as their vented counterparts, VRLA batteries eliminate the need for water additions and are typically much more compact.

Nickel-Cadmium Batteries

Another well-established type dating from about 1900, nickel-cadmium (Ni-Cd) batteries are longer lasting, more abuse-resistant, but more expensive than lead-acid. Manufacturers have augmented the traditional pocket plate designs over the last 30 years with newer designs, such as fiber plates and sintered-plastic bonded hybrids. Although their high initial cost keeps Ni-Cd batteries out of many price-sensitive markets, they have found niches in certain abusive applications, such as on mass transit rail vehicles. In the stationary market, Ni-Cd is used typically in high-temperature operation, where lead-acid life is much shorter and the overall life cycle cost of Ni-Cd is lower. Most recently, this battery type has found a place in telecom outside plant, where it is often installed in remote cabinets and subjected to very high temperatures.

Nickel-Metal Hydride Batteries

Scaled up from portable designs for electric vehicles, nickel-metal hydride (Ni-MH) batteries are another possibility for future use in energy storage and other stationary applications. Electrochemically very similar to Ni-Cd, larger capacity Ni-MH batteries have been developed using recombinant designs and limited electrolyte, to maximize energy density. Various manufacturers are currently producing these batteries, and the most notable use is for the new hybrid vehicles from Honda and Toyota. While this battery type shows some promise for general stationary applications, it seems likely that it will be overshadowed by lithium ion batteries, also under development. Work is ongoing to characterize Ni-MH for float operation, and at this stage a special charger would be required for this type of application.

Lithium Ion

Since they appeared in commercial production around 1993, lithium ion batteries have taken over more than 50% by value of the portable battery market. This phenomenal success seems to hold out great hope for a repeat performance in both automotive and stationary applications. Lithium ion electrochemistry is extremely simple, and this is one of the few non-aqueous battery systems on the market. This allows the production of hermetically sealed cells that require no routine maintenance, and also makes very high cell voltages practical. Many lithium-based cells operate in the 3-4V range and this is an important contributing factor to a very high energy density. They also have exceptional shallow cycling capability, providing over 250,000 cycles at 10% depth of discharge. For safety reasons, lithium ion batteries require electronic charge control, implemented at both the individual cell level and the overall battery level. While this adds to the battery cost, it also creates a ‘smart’ battery that requires minimal supervision. Lithium ion batteries are currently in pilot production, and trials in stationary applications are just beginning.

Sodium-Sulfur

Development work on sodium-sulfur (NaS) batteries has been ongoing for over 30 years. Finally, the difficulties in operating a battery at around 300°C appear to have been overcome, and a number of demonstration sites are in operation in Japan. In fact, the world’s largest battery is a 48 MWh NaS installation at Tokyo Electric Power’s Ohito substation, where there is not just one, but three units of this size. NaS batteries offer high energy density, but the safety features required for these high-temperature batteries also cause their power capability to be limited. Production is currently at a relatively low level, but when implemented on a large scale, this technology promises to be at about the same cost level as lead-acid, at least for high-capacity installations.

Flow Batteries

This category actually encompasses several electrochemical systems. They are characterized by having external tanks containing active material electrolytes that are pumped through an electrode stack, where the reaction takes place. Technologies in this category include sodium bromide-sodium polysulfide, vanadium redox and zinc-bromine. In some cases, the electrodes merely provide a means of transferring ions between the electrolytes and are essentially unaffected by deep discharges. These types therefore offer very good prospects for commodity storage applications. For a given power level (which is determined by the size of the electrode stack), the capacity is limited only by the size of the external electrolyte tanks. While flow batteries can theoretically be designed for high power discharges, this is not likely to be a cost-effective option. Production of these batteries is still rather limited, but they are already powering Malaysian villages (zinc-bromine), Japanese office buildings (vanadium redox), and will soon establish a new benchmark for the world's largest battery, when a 120 MWh sodium bromide-sodium polysulfide battery is commissioned in the UK later in 2001.

POWER VS. ENERGY

In most, if not all, battery systems, the quantity of active material determines the stored energy, while the electrode surface area determines the inherent power capability. To be sure, there are other design aspects that influence the rate at which this power can be removed from the battery, but these do not affect the basic relationship.

Power Density vs. Energy Density

In a number of battery technologies, designs are available for high power or low power discharges, and sometimes also for medium rates. In nickel-cadmium batteries, for example, the IEC 623 standard[2] lays down qualification criteria for (L)ow-, (M)edium-, (H)igh-, and e(X)tremely high-rate designs. Figure 2 shows the discharge characteristics of typical L and H types, in terms of the percentage of rated capacity that can be removed at different discharge times. The H cell type has the same rated capacity as the L, but the active material is distributed through a large number of relatively thin plates, while the L has a smaller number of thicker plates. The L-type consequently has a lower cost per watt hour. For short discharge times, however, it can clearly be seen that the H-type delivers a much higher percentage of its rated capacity, and as a result has a lower cost per watt.

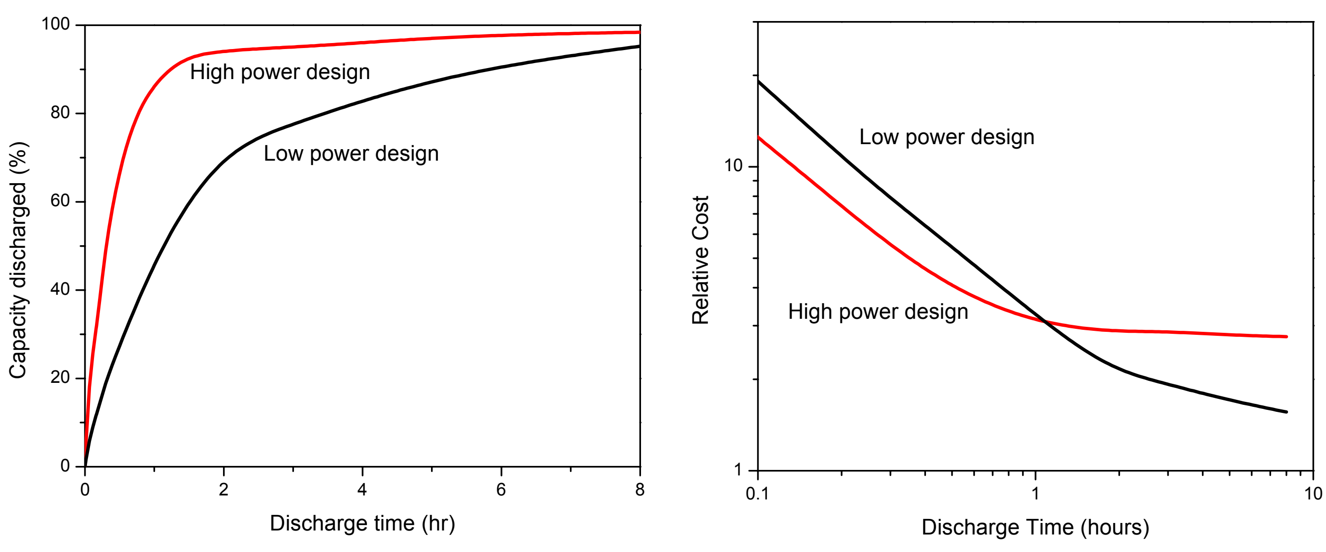

Figure 2 - Ni-Cd Cell Discharge Characteristics

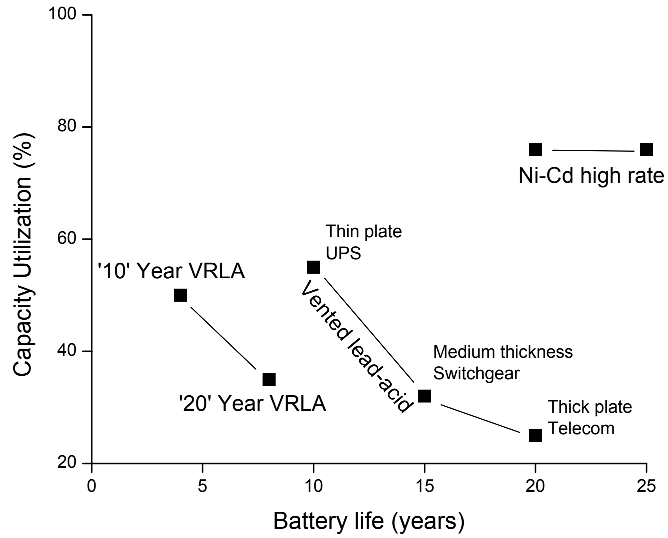

Figure 3 – Capacity Utilization vs. Life for 20-Minute Discharges

Power vs. Life

In the more prevalent lead-acid technology, the same relationship holds regarding power and energy in relation to the plate thickness, but the cost relationship is reversed, with thinner-plate batteries being less expensive per watt hour. Automotive batteries, for example, have the thinnest plates and the lowest cost per watt hour. It might be expected that this would result in only thin-plate designs being used, but their advantage is offset by shorter service lives. Indeed, there is a strong relationship between plate thickness and life, as shown in Figure 3.

The graph shows the typical percentage of rated capacity available from various lead-acid cell designs, as a function of their normal service life. This life is typically determined by the phenomenon of positive grid corrosion, which is an unavoidable side effect of normal charging. Thinner grids are more rapidly affected by corrosion, so thin-plate batteries have shorter lives. Thicker plates require much heavier grids, which involves a considerable amount of extra lead, hence the increased cost. In contrast, the plate hardware of nickel-cadmium batteries does not deteriorate over life, so these batteries can be designed with very thin plates without sacrificing life.

One of the other new developments in the stationary battery market is the scaling up of lithium ion designs. This technology, already hugely successful in the portable battery market, shows great promise for energy storage and other applications. Part of the development work has been to produce high-energy types for electric vehicles and high-power versions for hybrid electric vehicles. To complete the application spectrum, mid-range designs are also available. The relative power and energy densities of these designs are shown in Table 2. By comparison, high-quality VRLA batteries have energy densities in the range of 50-80 Wh/liter and power densities of roughly 500 W/liter.

Table 2 - Power and Energy Density of Lithium Ion Designs

Cell Design	Energy Density (Wh/liter)	Power Density (W/liter)	P/E Ratio
High Energy	321	920	2.9
Mid Range	300	1930	6.4
High Power	234	2620	11.2

DG BATTERY CHOICES

It has already been shown that batteries used to support distributed generation will, for the most part, have to supply high power, provide good life under shallow cycling conditions and operate well at high temperatures, while being compact and easily transportable. Unfortunately, today's batteries cannot easily meet this combination of characteristics.

Lead-acid batteries will frequently be chosen for this application, at least for the time being, simply because they are inexpensive and readily available. However, high-power versions have short operating lives, especially if required to operate at high temperatures. VRLA batteries are reasonably compact compared to vented types, and have provided good results when cycled at partial states of charge[3]. Against this, they have an even shorter life than their vented counterparts.

Nickel-cadmium technology can offer both high power and long life, but at a relatively high initial cost. These batteries typically use a flooded construction and are therefore larger than VRLA types. However, for high temperature operation, their life cycle cost becomes much more favorable and they can be a good choice, particularly in critical applications.

Flow batteries and high temperature designs like sodium-sulfur are not expected to be particularly well suited for this application, since they are limited in their high power capability. Flow batteries have the additional disadvantage of having a rather low energy density.

Of the new technologies under development, lithium ion stands out as the most promising for distributed generation applications, with the high power designs meeting all the characteristics listed above. The biggest question mark for this technology is over the price, which is highly volume-sensitive. A number of industry projections are pointing to a life cycle cost that is competitive with high quality lead-acid, but it will take a number of years to get to that point.

CONCLUSIONS

Distributed generation is about to enter a phase of rapid and large-scale deployment. Microturbines are already in production, and fuel cells are at an advanced stage of development. Energy storage complements distributed generation by compensating for lags in generator response and by providing peak power capability for loads that exceed the generator output.

Today's batteries offer compromises for this application. Lead-acid batteries will frequently be used because of their low initial cost, but high-power versions have short operating lives. Nickel-cadmium batteries cost more and require more space, but will find a niche in critical applications, particularly at high operating temperatures, where life cycle cost is more important.

Of the battery technologies under development, high power lithium ion offers the most promise for supporting distributed generation. In a few years, these batteries will be able to satisfy all the electrical and physical requirements, with a life cycle cost that should be competitive.

REFERENCES

1. Willis, H.L., "*Energy Storage Opportunities Related To Distributed Generation*," proceedings of the IEEE Power Engineering Society Summer Meeting 2000, Seattle, WA, July 2000

2. IEC 623-1990, "*Vented nickel-cadmium prismatic rechargeable single cells*"

3. Corey, G.P., "*Battery Charging in Float vs. Cycling Environments*," proceedings of Battcon 2000