

Battery Options for Critical Photovoltaic and Hybrid Power Systems

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Abstract

The solar power market is experiencing rapid growth as photovoltaic (PV) panel prices have continued to fall. While much of this growth is in grid-connected residential systems in which batteries are not required, there is a large market for off-grid applications, with some of these involving hybrid power schemes such as PV-diesel systems. The vast majority of residential, rural and low-end commercial systems use inexpensive lead-acid batteries, but there is a growing segment for powering critical systems such as rail signaling and telecommunications repeater stations. Some of these installations have limited accessibility and issues such as battery weight and maintenance interval become important.

This paper describes present and future battery options for these critical PV applications. In addition to lead-acid batteries the existing options include the latest developments in nickel-cadmium, while developing technologies such as nickel-metal hydride and lithium ion are also discussed.

Introduction

The worldwide PV market is showing dramatic growth, with production in 2002 rising a dramatic 44% over the previous year to 562 MW, as shown in Figure 1. This growth has resulted in a corresponding drop in panel costs, with typical factory prices now below US\$3 per watt.

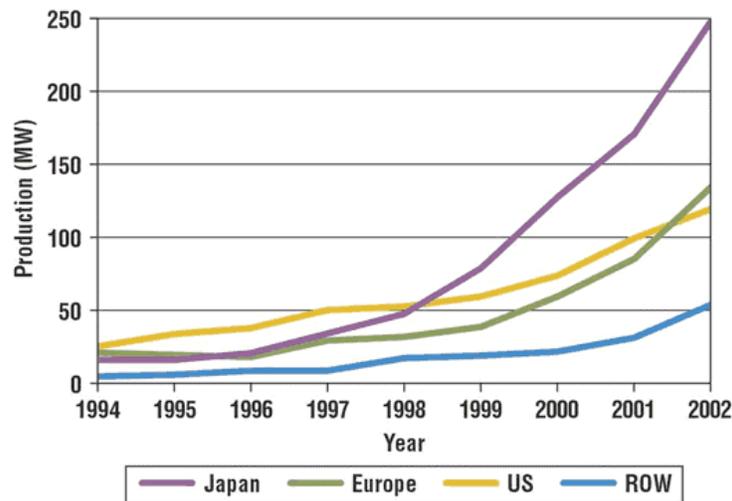


Figure 1: World cell/module production, consumer and commercial, 1994-2002 (MW)

Source: PV News, Vol. 22, No. 3, 2003

Of course, much of the PV market is in grid-connected residential systems and small consumer appliances, as shown in Figure 2¹. Considering just the sectors for ‘communications and signaling’ and ‘PV/diesel, commercial,’ the size of the worldwide PV market for such installations is 105 MW, and a portion of these would be considered to be critical. This figure represents the peak power output of the PV panels, so the steady state loads being powered in these applications can be conservatively estimated at around 35 MW. If the average system has a 2-day autonomy (most remote systems have much more) and the typical dc voltage is 24 V, this works out to a total battery capacity for such systems at 70 million ampere hours in 2002 alone.

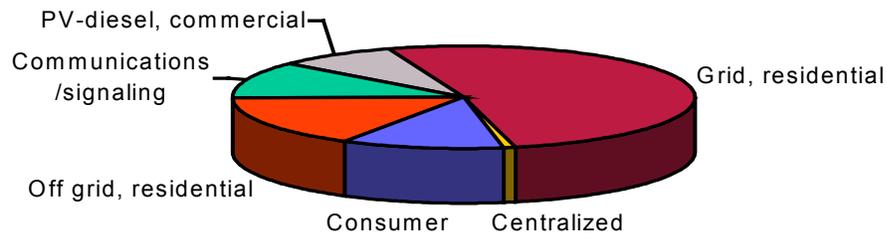


Figure 2: Worldwide 2002 PV installations by market sector

Remote installations

The Canadian population is concentrated in relatively small areas, with the majority of the landmass being very sparsely populated. Bringing adequate communications to remote communities results in the need for mountaintop repeater stations that may only be accessible by helicopter. Also, cross-country rail lines pass through vast uninhabited swaths of countryside with no access to power, yet reliable communications and signaling systems are a must. PV power is a natural choice for such installations, but the criticality of these applications and the often-demanding operating conditions dictate that a rugged and reliable battery be selected.

Smaller installations are simple standalone systems with a PV array and battery. A small wind generator may also be added in some cases. Battery autonomy may be just a couple of days for less critical systems to 30 days or more for life safety systems with limited accessibility. For systems in the far north several months of battery run time may be required.

As the supported loads increase in power it becomes less economical to support them with a standalone system. In such cases it is typical to revert to a hybrid PV-generator system. This allows a much smaller battery to be used: the system runs on PV/battery power whenever possible and the generator is started when the battery reaches a low state of charge. This arrangement allows the generator to operate at peak efficiency to support the loads and charge the battery to a high state of charge.

The requirements for batteries in both standalone and hybrid applications can be summarized as follows:

- High reliability and availability
- Ability to operate at high temperature with little effect on operating life
- Good capacity availability at low temperature and no risk of freezing
- High charge efficiency and low rate of self discharge
- Good shallow cycling capability for standalone systems
- Good deep cycling capability for hybrid systems
- Minimal maintenance
- Low weight and volume if transported by light airplane or helicopter
- Favorable life cycle cost

The last item is, of course, the most important, since it incorporates elements of all the other points in addition to costs associated with battery failure and unplanned replacement.

Traditional battery options

With these requirements in mind, it is possible to compare the characteristics of various battery types for critical PV applications, including both standalone and hybrid installations.

Lead-acid

The choice for the vast majority of stationary battery installations, including PV systems, lead-acid batteries have a low initial cost combined with good performance under reasonable operating conditions. Golf cart or deep-cycle marine batteries have the best price to performance ratio for many PV applications, especially off-grid residential

systems. Despite such favorable attributes, these batteries exhibit serious shortcomings when operated under more extreme conditions. Their thin plate structures corrode relatively rapidly at high temperatures and their short lives result in frequent battery replacement – a distinct problem for a mountaintop system.

There is often a tradeoff with lead-acid technology between cycle life and maintenance requirements. Typical plate alloys using calcium exhibit low maintenance but cycle poorly, while cells with lead-antimony grids cycle well but require frequent water additions. Improvements can be made with tin additions to lead-calcium alloys or the use of low-antimony alloys with additional hardeners such as selenium, but such cells are better suited to the shallow cycling of standalone systems rather than daily deep cycling in hybrids. Tubular positive plate construction gives better cycling performance than traditional pasted plate types, but such cells are not widely available in North America and tend to be rather expensive.

Valve-regulated lead-acid (VRLA) batteries tend to have better cycling capability than their vented counterparts, since the compression of their plate stacks minimizes the shedding of active material. The oxygen recombination reaction in these cells also inhibits capacity imbalances between the positive and negative electrodes, so these cells function quite well in partial state of charge (PSOC) cycling. Of the two types of VRLA technology, absorbed glass mat (AGM) cells are smaller and lighter, while cells with gelled electrolyte have better thermal management and may incorporate tubular positive plates for better cycling performance. On the whole, however, VRLA cells are more temperature-sensitive than vented types and generally have shorter operating lives.

Nickel-cadmium

Nickel-cadmium (Ni-Cd) batteries have a reputation for long life and high reliability, but typically have a high initial cost. Although they cycle quite well and have a number of other attractive features, they have never been anything more than a small niche product in PV applications. This lack of success has been because there was no one product that met all the requirements listed previously in this paper.

Traditional pocket plate cells have an iron mass expander in their negative active material. During deep cycling at high temperature a portion of this iron is dissolved into the electrolyte. It then reacts with the positive active material to form an electrically inactive compound, resulting in a loss of capacity and premature aging. Other Ni-Cd technologies do not use an iron expander. Newer fiber plate Ni-Cd cells have better cycling characteristics but also need more frequent water additions. Cells with sintered positives and plastic-bonded negatives combine excellent cycling with very low maintenance, but these plate types are essentially for high-power, short-duration discharges and are very expensive for low-power, long-duration use.

A recent advance has allowed the iron migration problem to be overcome in pocket plate cells. This involves the substitution of a synthetic rubber material for much of the iron mass expander to produce a ‘low-iron’ negative active material. The result is a design that can provide up to 8000 cycles, or 20 years of operation, at 15% depth of discharge (DOD).

Furthermore, this technology has been combined with fiber mat separators to give a flooded, partially recombinant design that can operate for several years in a PV application without requiring water additions. These features, combined with the ruggedness of pocket plate technology, meet many of the needs for batteries in critical PV applications.

But what of other areas, such as charge acceptance at high temperatures and overall charge efficiency, where Ni-Cd has traditionally been viewed as rather weak? These characteristics have little or no impact in normal standby applications but assume much greater importance in PV operation.

The traditional view is that Ni-Cd batteries require 140% charge input to store 100% of rated capacity, whereas lead-acid only needs 110-115% charge input. On the surface it would appear that the Ni-Cd is only 71% efficient, while lead-acid is around 90% efficient. These numbers, however, ignore actual usage patterns. With voltage controlled charging and limited charging time it is normal for any battery system with an aqueous electrolyte to stabilize at less than 100% state of charge (SOC). When this type of operation is taken into account a very different picture emerges, as shown in Figure 3. This shows the ratio of ampere-hours charged to ampere-hours discharged under simulated PV operation. Since voltage controlled charging is used the overcharge amount is controlled by what the battery will accept.

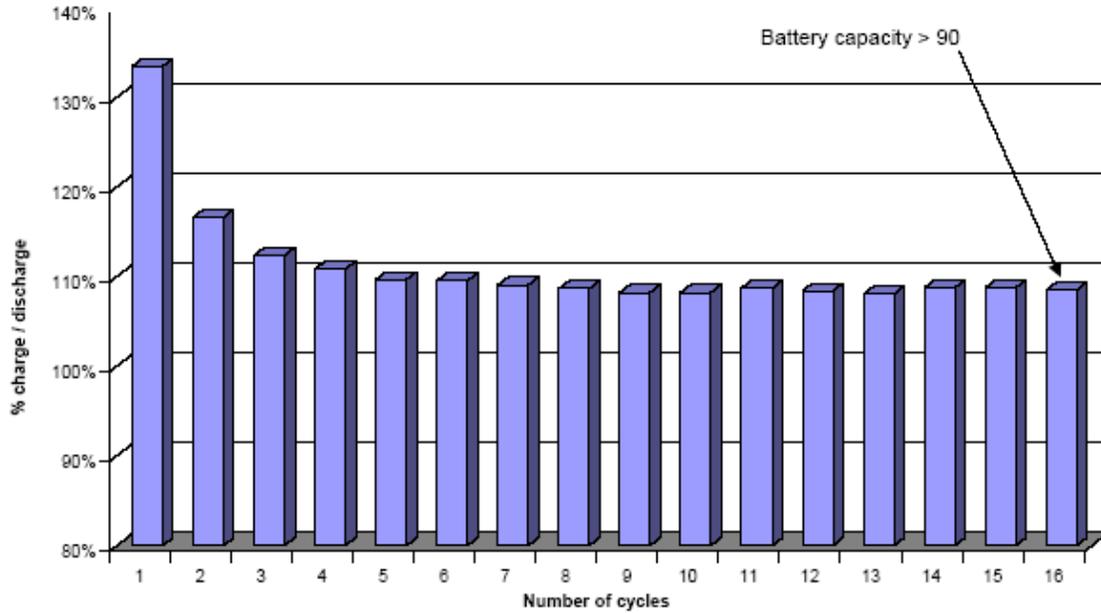


Figure 3: Overcharge capacity during cycling at 15% DOD with 1.55 V/cell charge voltage – Ni-Cd pocket cells with low-iron negative active material

The graph shows that the overcharge ratio on this type of cycling quickly stabilizes at less than 110%, while the available capacity remains above 90%. The charging at this point is therefore better than 90% efficient. This type of experiment has been repeated at various temperatures and for different depths of discharge. Charging efficiency at 50% SOC has also been measured, to determine how the battery will behave when cycled at low SOC during winter months when charging energy is scarce. The results of this work are shown in Table 1 below.

Table 1: Operating characteristics for Ni-Cd pocket cells with low-iron negative active material under PV operation up to 40°C

Daily DOD	Typical Autonomy	Charge Voltage*	Expected SOC	Ah efficiency at high SOC	Ah efficiency at 50% SOC
5 to 10%	>= 5 days	1.50 V/cell	>= 90%	82 to 90%	>96%
10 to 15%	3 to 4 days	1.55 V/cell			
15 to 25%	2 to 3 days	1.60 V/cell			

* Higher voltage required for prolonged operation at very low temperatures

With winter temperatures in many parts of Canada frequently dropping to -40°C or below, low temperature performance and freeze resistance can be extremely important for a PV battery. Figure 4 shows the discharge capability of this battery type at -40°C when using more concentrated ‘Arctic’ electrolyte. The curves show that a battery with 5-10 days of autonomy (most critical systems are sized with a much larger battery), 80-90% capacity is available from this battery.

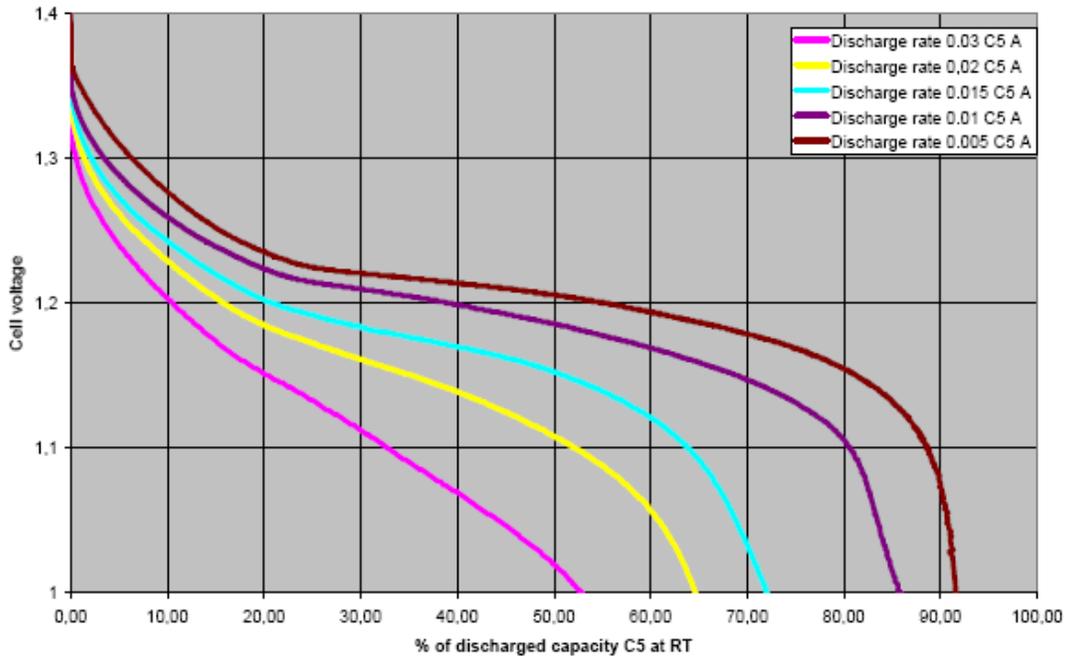


Figure 4: Performance curves for Ni-Cd pocket cells with low-iron negatives at -40°C

Also of extreme importance is that such cells are freeze resistant. The potassium hydroxide electrolyte does not take part in the cell reaction, so its concentration remains virtually constant throughout discharge and the freezing point does not increase, as is the case for lead-acid cells. Even at extremely low temperatures the 'Arctic' electrolyte does not freeze solid. Figure 5 shows a battery of this design that was subjected to a freeze test. The battery was fully discharged, then cold-soaked for 16 hours at -63°C. At the end of this period the electrolyte temperature was -53°C and the electrolyte was slushy rather than frozen. Upon warming to room temperature no physical damage was found and the battery functioned normally.



Figure 5: Cold soak test at -63°C

From this information it can be seen that a Ni-Cd pocket plate battery with low-iron negative active material has characteristics that are very well suited for PV applications, with the ability to operate reliably with little or no attention for years at a time. Considering also that Ni-Cd batteries are lighter than their lead-acid counterparts, this makes them much easier to transport to remote locations such as mountaintops.

Advanced battery options

Having considered traditional battery technologies, what of newer battery types? Consumers are quite familiar with nickel-metal hydride (Ni-MH) and lithium ion batteries for small handheld devices such as laptop computers, PDAs and cell phones. What is the prospect of such batteries being used widely in PV applications?

Nickel-metal hydride

Ni-MH cells share many characteristics with Ni-Cd, in large part because the electrochemical potential of hydrogen is very similar to that of cadmium. Rather than containing this hydrogen in pressurized bottles, as in nickel-hydrogen cells, it is absorbed into a metal alloy in the form of a hydride. A variety of metal mixtures can be used in this negative electrode and they are generally designated as AB₂ or AB₅ types, with AB₅ being more commonly used. The positive electrodes of these cells are chemically identical to those in Ni-Cd cells – although the plate structure may be somewhat different – and they share the same cell voltage of 1.2 V.

The most prominent application for large-scale Ni-MH batteries is in hybrid electric vehicles such as the Toyota Prius. The main advantage over lithium ion for these vehicles is simply that Ni-MH is in industrial production now and lithium ion is not. Lithium ion is widely expected to supplant Ni-MH in hybrid vehicles, just as it did with laptop computers in the late 1990s and with cell phones a few years later. Although this is a common trend for Ni-MH that is likely to be repeated eventually in PV applications, Ni-MH remains an attractive option for PV at present, subject to a few constraints.

Ni-MH designs are typically based on the oxygen recombination principle, as with VRLA. This makes them maintenance-free with respect to the electrolyte, and they also have no gas emissions in normal operation. As with VRLA, they operate well under PSOC cycling because the recombination reaction limits plate imbalances. Ni-MH cells have inherently higher energy density than Ni-Cd, and with no requirement for a large electrolyte reserve they can be much smaller and lighter than Ni-Cd or lead-acid.

The charging characteristics of Ni-MH are quite similar to Ni-Cd – which is understandable, bearing in mind that they share the same positive electrode chemistry. However, Ni-MH cells tend to be more sensitive to overcharge and require electronic controls at the string level. Fortunately, standard PV controllers provide the necessary charge control functions and no additional circuitry is required.

Ni-MH technology performs well over a narrower operating temperature range than Ni-Cd, showing less capacity availability at low temperatures and faster aging at the high end. It is also important to consider the characteristics of each individual design. For example, typical consumer cylindrical cells tend to have higher self-discharge and more susceptibility to overcharge than larger prismatic designs. The latter types should easily give 10-15 years of trouble-free operation under moderate temperature conditions in a PV application, albeit at a relatively high initial cost. With this in mind, Ni-MH can offer distinct benefits for PV applications where battery volume and weight are critical, and where transportation costs offset the additional cost of this technology.

Lithium ion

From an electrochemical viewpoint, lithium ion seems to be a near-ideal technology for PV systems. These cells have non-aqueous organic electrolytes – indeed the cell voltage is so high, averaging around 3.6 V, that water would immediately dissociate into hydrogen and oxygen if it were present. Water is the main source of charging inefficiency in aqueous technologies such as lead-acid, Ni-Cd and Ni-MH, through the electrolysis and oxygen recombination reactions. With such side reactions being absent in lithium ion, coulombic charging efficiency is virtually 100% and the cells operate at an overall energy efficiency of better than 95%. They can also be hermetically sealed and are completely maintenance-free.

While this seems to be an ideal characteristic for a PV battery, allowing the most efficient use of limited charging energy and the smallest possible array size, there is a flip side to this coin. Water in the electrolyte provides a means for dissipating excess charging energy, which can be a major factor in PV systems in higher latitudes. Lacking in an

inherent mechanism for 'spilling' excess charging energy, lithium ion batteries must have this function provided by electronic means.

Charge control electronics must be installed to monitor the voltage and temperature of each individual cell. In addition to providing for routine balancing of cell voltages, these circuits will cause a reversible power switch such as a contactor or MOSFET to open if a fault condition is detected. This operation is certainly compatible with PV system operation, but the problem is with the power consumption of the electronics, since this represents a form of self-discharge.

With the current state-of-the-art, the electronic self-discharge represents several percentage points of battery capacity per day, as compared to a few percent of self-discharge per month for most other battery types. This makes these batteries much less suitable for PV applications with many days of battery autonomy. To be sure, it is likely that charge control electronics will eventually be developed with much lower power consumption, but this factor, combined with the high present cost of large format batteries, will severely limit the use of lithium ion in PV applications for the present.

Conclusions

With the continuing decline in solar panel costs, PV applications are moving into the mainstream. While lead-acid batteries will continue to be widely used in most installations, the criticality and remoteness of some systems provides a rationale for using a more reliable technology. In such cases the additional initial battery cost is frequently offset by a lower life cycle cost.

Nickel-cadmium technology has been given a new opportunity in these applications by the introduction of a low-maintenance pocket plate design with low-iron negative active material. Advanced battery technologies will also start to be seen. Lithium ion will become prominent in the longer term but is limited at present by high costs and the excessive power drain of charge control electronics. Nickel-metal hydride batteries have better short-term prospects for sites where accessibility is a problem and their low volume and weight can be a benefit.

Reference

¹ Paul Maycock, '*PV Market Update*,' Renewable Energy World, July-August 2003