One Size Doesn't Fit All: Lithium-Ion Technology Choices for Standby Applications

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Abstract

Spurred by successes in electric vehicles and large-scale grid-connected energy storage systems, there is growing interest in the deployment of lithium-ion batteries in traditional standby applications. Making a proper assessment of the suitability of such batteries is filled with complexity, however. To start with, the term 'lithium-ion' covers a wide range of electrochemical systems with an alphabet soup of abbreviations, such as NCA, NMC, LFP and LTO, to name just a few. These systems have different characteristics with respect to calendar life, operating temperature range, energy density, power capability, cell-level safety and others. This paper outlines the pros and cons of the different lithium-ion technologies for UPS, telecom outside plant and utility critical power applications, and provides guidance on system design for successful operation.

Introduction

Lithium-ion (Li-ion) technology is ubiquitous in consumer portable devices, and has now been successfully deployed in a wide variety of electric vehicles. Furthermore, while Li-ion remains a bit of a curiosity in the standby battery world, a check of the DOE Energy Storage Database[1] reveals that over 1.1 gigawatts of Li-ion-based grid-connected energy storage has been deployed worldwide since 2009 or is under construction; sufficient to power approximately 770,000 homes. Such systems have moved well beyond the demonstration phase and are being deployed by project developers under standard commercial terms.

Inevitably, such successes have created considerable interest in the possibilities for Li-ion in standby applications, and some early adopters are moving forward with systems in a variety of applications. However, there remains considerable confusion in the minds of many prospective users regarding the wide range of technology choices available, including electrochemistry, cell design, and system architecture. The intent of this paper is to shed some light on those choices, providing pros and cons of the various Li-ion electrochemistries and guidance in other areas.

Li-ion Technology

A Family of Electrochemistries

As discussed in the author's Battcon 2008 paper[2] the term "lithium-ion" describes a broad range of electrochemistries that are characterized by the exchange of lithium ions between the electrodes on charge and discharge. Those ions are inserted into the physical structure of the various electrode materials, typically by intercalation (insertion between layers), and the systems are characterized by the absence of metallic lithium.

Materials for the positive electrode, commonly called the cathode, include transition-metal oxides and phosphates. The active material in the negative electrode, commonly called the anode, is typically graphite or another form of carbon, although a few systems make use of lithium titanate material and some are beginning to transition to materials based on silicon. Figure 1 shows a sampling of electrode materials, plotting their potential versus lithium metal against their specific capacity.

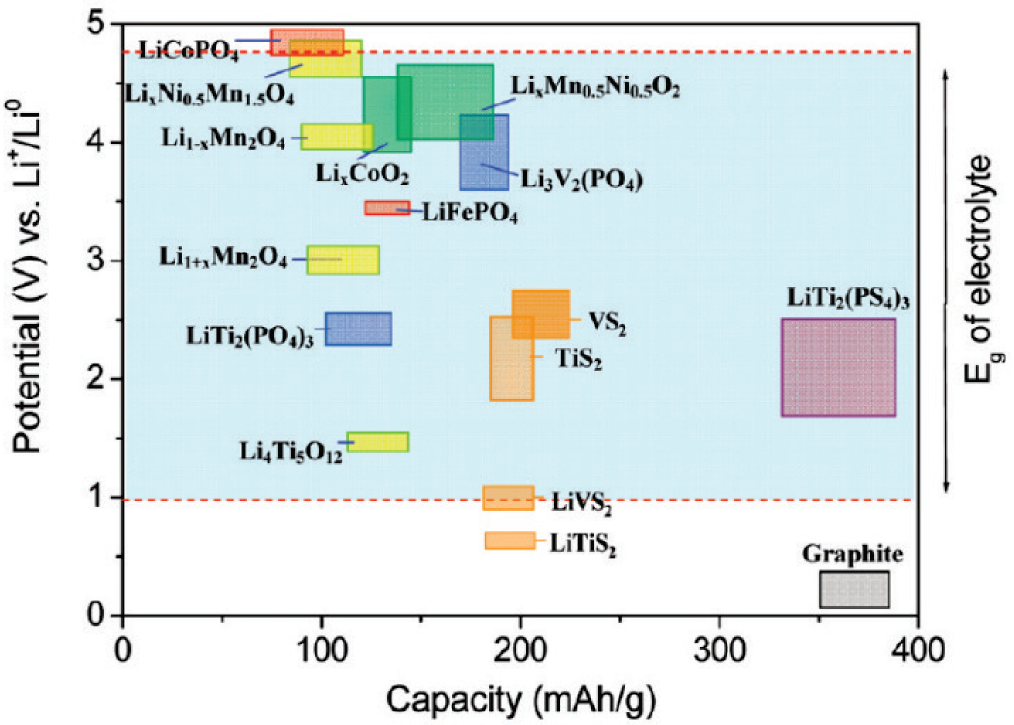

Figure 1. A sampling of Li-ion electrode materials

For any combination of materials the cell voltage is the difference between their electrode potentials, with some materials showing a strongly sloping discharge voltage characteristic and others being flat. These differences are illustrated in Figure 2 below.

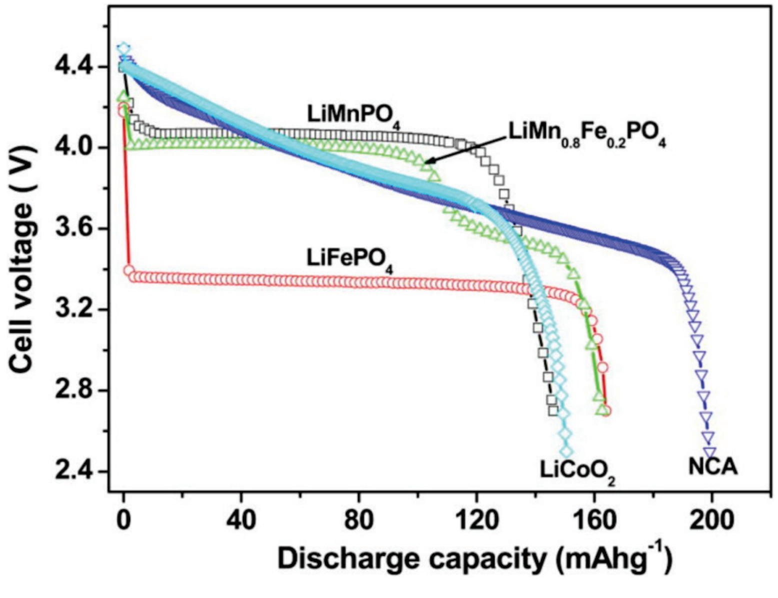

Figure 2. Cell voltage curves for various Li-ion chemistries

Positive active materials may be simple compounds, mixed-oxide compounds, or blends of two or more materials. For the purposes of this paper the following common positive materials, all combined with graphite negatives, will be discussed:

- **NMC** lithium nickel-manganese-cobalt oxide (the standard technology used in consumer portables)
- **NCA** lithium nickel-cobalt-aluminum oxide
- **LMO** lithium manganese oxide
- **LFP** lithium iron phosphate

Chemistry Pros and Cons

Figure 3 below provides a simple ranking of the subject chemistries for a range of attributes that may be useful in standby applications. Better relative performance is indicated by positions at the outside edge of each chart and worse performance by positions towards the center. All technologies can be designed for high-power, short-duration or high-energy, long-duration discharges, have cycle life in the thousands of deep cycles, exhibit 95+% round-trip energy efficiency, and are hermetically sealed. The attributes that are considered in the charts are as follows:

- Calendar life at 20°C to 25°C
- Calendar life at high temperature (>40°C)
- Capacity availability at low temperature
- Safety of positive active material
- Energy density
- Power density

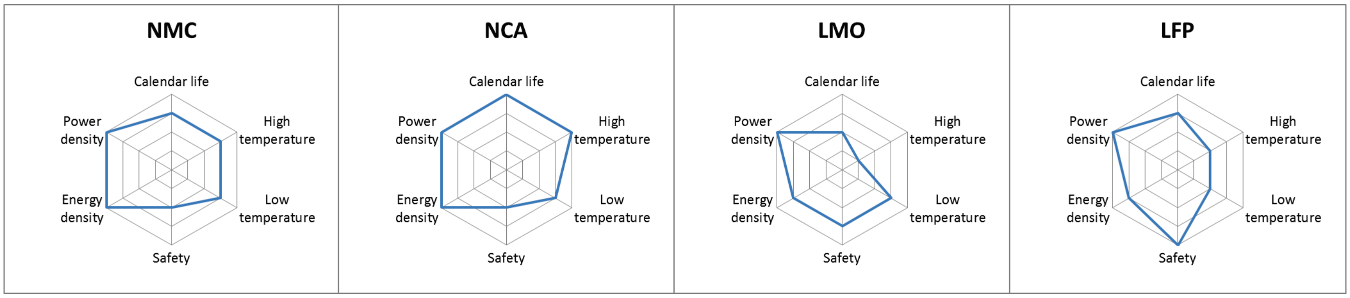

Figure 3. Characteristics of Li-ion positive active materials

Perspectives on Safety

Two recent Battcon papers[3,4] have provided a good background on Li-ion safety and the importance of taking a holistic system approach to this subject. These papers show that safety is not absolute and that the probability of any given event can be expressed statistically. Furthermore, it is possible to design Li-ion battery systems with a high level of safety, regardless of whether a 'safer' active material is used. Armed with this knowledge, it becomes easier to look at the particulars of an application and to place the safety statistics in context.

Choosing an appropriate level of safety for an application depends on a number of factors, such as

- The installed battery energy in a single location
- The proximity of personnel to the battery area, and whether those personnel are trained
- The presence of dedicated fire safety systems and containment structures

For example, a battery on a crowded subway car that stops in tunnels must exhibit a lower probability of a safety event than one in a customized shipping container that is installed behind the fence at a utility substation. For the former it would be prudent to choose active materials that exhibit a higher level of intrinsic safety, while for the latter the system designer has more freedom to consider other application drivers, such as energy density or calendar life. By following this approach, operational safety can be treated as a selection criterion, to be ranked alongside other application considerations.

System Design Considerations

A successful deployment of Li-ion technology requires recognition of the fundamental differences between Li-ion and the much more common aqueous technologies of vented lead-acid (VLA), valve-regulated lead-acid (VRLA) and nickel-cadmium (Ni-Cd), as discussed in a Battcon 2010 paper[5]. That paper concluded that the use of cell-level electronics with Li-ion, coupled with the fact that Li-ion battery strings will disconnect themselves from the dc bus to preserve safety functions or to protect the battery against overdischarge, requires a modular system architecture with multiple parallel strings and some level of redundancy.

Field experience with Li-ion batteries has shown that the vast majority of battery failures derive from the electronics and not the cells. While the mean time between failures (MTBF) of such systems is impacted by the electronics, the mean time to repair (MTTR)—typically replacement of a printed-circuit board—can be quite short and the corresponding availability can be very high. The statistical treatment of battery failures was the subject of the author's Battcon 2005 paper[6].

Cell design can also play a part in how well a particular Li-ion technology fits in a stationary application. For example, Li-ion polymer cells feature flat electrode plates that are bonded together by a polymer matrix, with the electrode stack being contained in a thin Mylar 'pouch'—essentially a plastic bag—that adds very little volume to the cell. Such a construction can provide optimized energy density and power density at system level; on the other hand, maintaining an effective seal around the cell terminals is more challenging and may limit the calendar life.

Application Examples

The examples in this section show how an assessment of application drivers can lead to a reasoned choice of Li-ion chemistry, and thus to an optimized system. Examples are provided to show the benefits that Li-ion technology can provide in specific situations.

Telecom Outside Plant

Battery deployments are accelerating in telecom outside plant applications, particularly for wireless base stations in emerging economies. Such installations may be subjected to frequent grid outages, with the associated cycling causing traditional VRLA batteries to fail quickly and providing a driver for deployment of Li-ion technology. Figure 4 below shows the needed attributes for this application along with the chemistry characteristics from Figure 3.

In this case the main drivers are for long calendar life, especially at high temperature, and high energy density. A high level of safety is always important, and can be assured at system level, but in this case the relatively small size of each installation does not push the technology choice to consider safety at the electrochemistry level above all else. It can be seen that NCA technology is a good fit for this application.

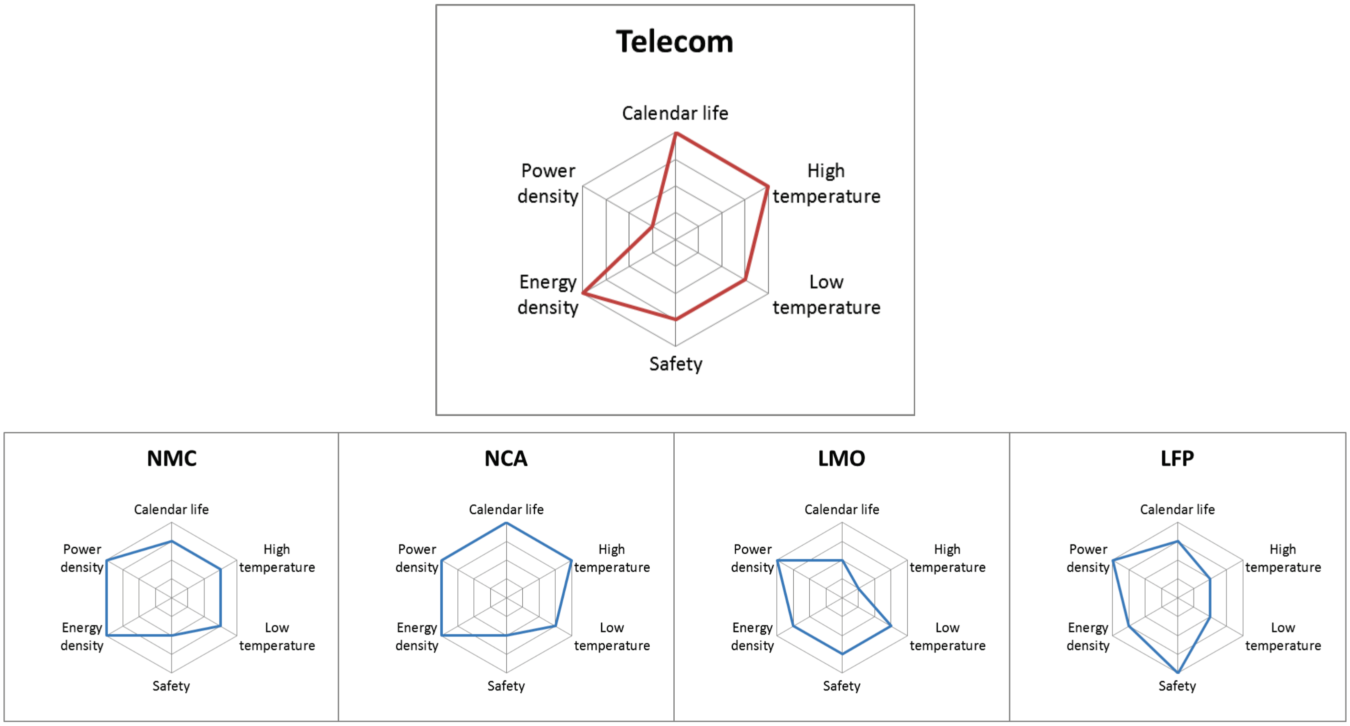

Figure 4. Telecom application needs compared to Li-ion technology characteristics

An operator in India today uses Li-ion batteries in its wireless telephone network. They are installed in remote terminal sites that are normally connected to the ac grid where the batteries provide several hours of autonomy. The types of remote terminals include Ground-Based Masts (GBM) or outdoor cabinets—see Figure 5.

With at least 4 hours of autonomy needed, the most compact and lightweight Li-ion battery is best for handling and installation logistics. This is particularly important in the GBM type installations where the batteries are lifted 6 meters (20 feet) to their compact shelf positions.

Figure 5: GBM (left) and outdoor cabinet (right) with NCA Li-ion batteries (Courtesy: Reliance Jio Infocomm Limited)

Additionally, these sites are not climate controlled and the temperature is typically very high. In some areas, power outages are frequent (up to 16 hours daily with several battery discharge cycles). In that case, the high temperature survivability of an NCA Li-ion battery is most important to minimize the relatively high cost associated with battery replacement in these remote sites.

The data buffer, part of the Li-ion battery's 'smart' feature, is communicated to the rectifier shelf controller. The data reported from each battery unit includes the maximum charge/discharge current allowed, the operating mode, the available capacity, the state of health and the alarm state. This data is used for feedback control of the rectifier charge current and power system diagnostics. In this integrated power system, this data processing contributes to the high availability of the battery.

For these remote sites the equipment is located in unmanned locations and only accessible by authorized and trained technicians. In that case, high-temperature calendar life and cycling capability are more important than inherent safety of the electrochemistry. In any case, redundant safety features included in the electronics mitigate the risk of thermal runaway.

Data Center UPS

The dc design of large UPS systems most closely resembles the grid-connected energy storage systems that have been so successfully deployed around the world. Li-ion technology offers a smaller footprint and a dramatic reduction in weight, especially for short run times, plus longer operating lives and the ability to cope easily with large numbers of small 'hits' that can be damaging to lead-acid batteries. Figure 6 shows the required attributes for this application, again compared with the Li-ion chemistry characteristics.

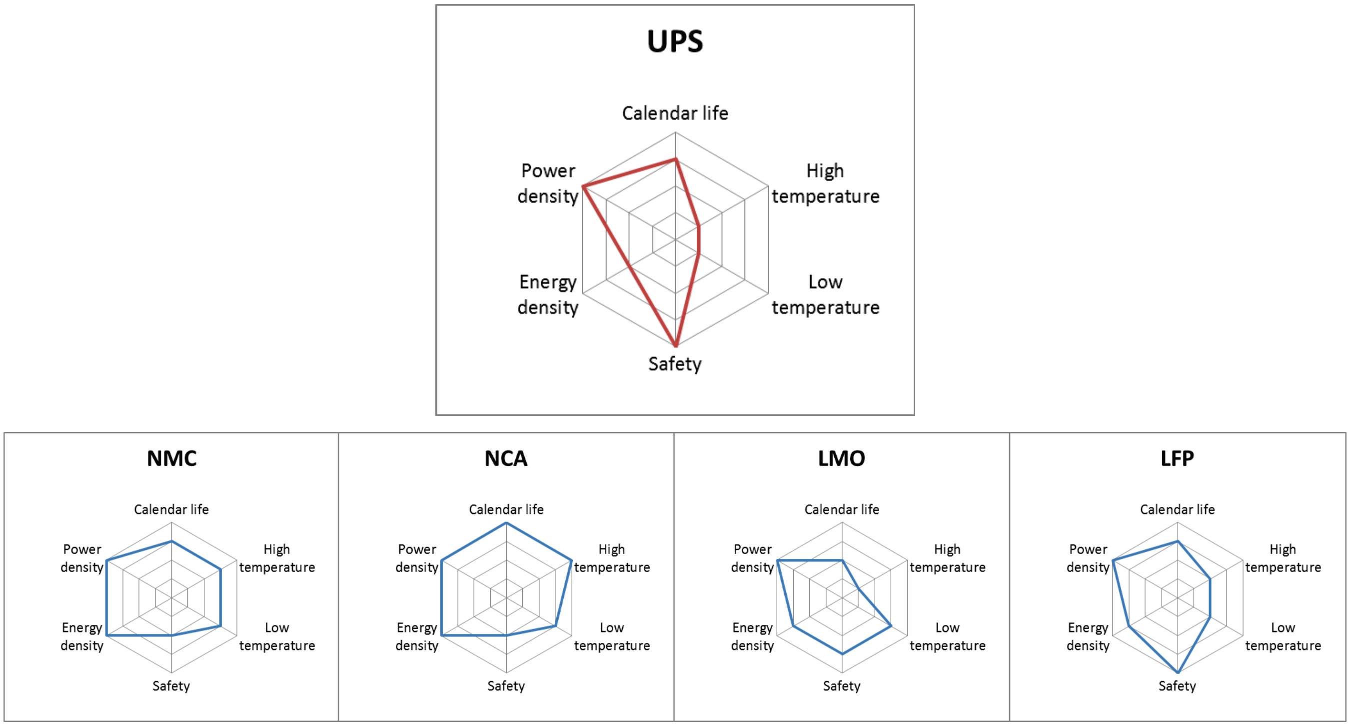

Figure 6. UPS application needs compared to Li-ion technology characteristics

For data centers the battery calendar life should ideally match that of the UPS equipment, typically in the 15- to 20-year range, and this is well within the capabilities of many (but not all) Li-ion designs. The battery operates under controlled conditions, so characteristics at high and low temperature are not relevant. Power density is extremely important as one would expect for UPS. Electrochemical safety is also highly ranked in this example because data centers are manned and the installed battery energy is rather large, despite the fact that the batteries are normally installed in a separate room. It can be seen that LFP characteristics are a very close match for the application requirements. An additional benefit of LFP technology is its very flat discharge voltage characteristic (see Figure 2), providing a relatively narrow operating voltage window and stable discharge current in constant-power applications.

Being able to optimize cells for high-power short-duration discharges, without affecting calendar life, is an important feature of Li-ion technology in this application. This allows a lower-capacity, much lighter battery to be installed for a given application, as demonstrated in the following example.

This example is for a 500 kVA UPS operating at 0.8 power factor with 90% efficiency, requiring 444 kW_b. A 5-minute run time is required, based on performance at the beginning of life. The comparison here is between a high-performance front-terminal VRLA product commonly supplied for UPS applications in high-density cabinets, and a rack-mounted high-power LFP-based Li-ion battery. Two VRLA cabinets and four Li-ion racks are required and their footprints are shown in Figure 7.

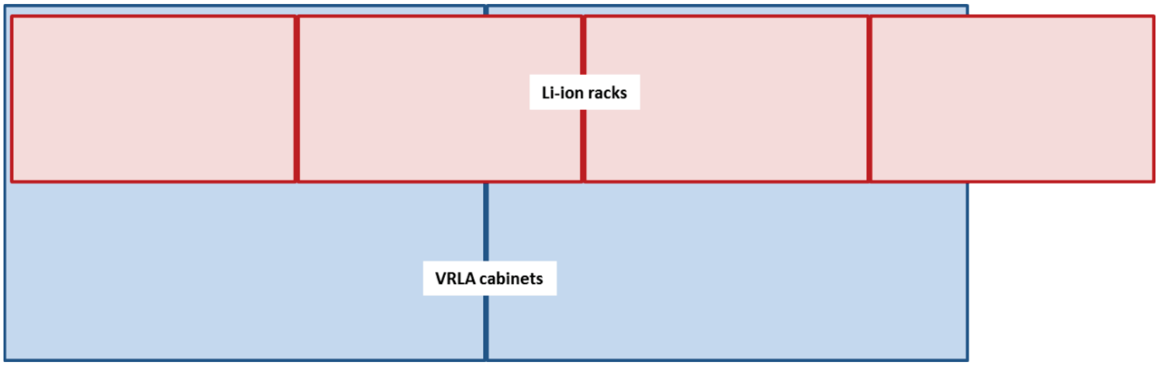

Figure 7. Footprint comparison for 5-minute UPS application

In this example the LFP battery footprint is 45% smaller and its weight is 72% less. Depending on the specifics of the application it is not unusual to see higher reductions in footprint and weight. These savings can translate into much lower infrastructure costs for new installations.

At the time of writing this paper the cost of a typical Li-ion system is significantly more than that of a high-power VRLA battery. However, when the longer life and lower infrastructure costs of the Li-ion system are considered the total cost of ownership is often lower.

Utility Critical Power Application

Typical substation battery installations are not space-constrained and the commonly used vented lead-acid and nickel-cadmium batteries provide long service life and high reliability. There are thus no real drivers for the use of Li-ion in substation applications. However, there can be critical-powering applications in power generation, particularly where emissions-control systems are being retrofitted to existing plants, where very limited space is available for a battery system. This was the situation faced by Southern Company at a number of their generating stations, where they needed secure power for equipment like bag houses and scrubbers but had very little space available. Their application needs are summarized in Figure 8, once again compared with the Li-ion chemistry characteristics.

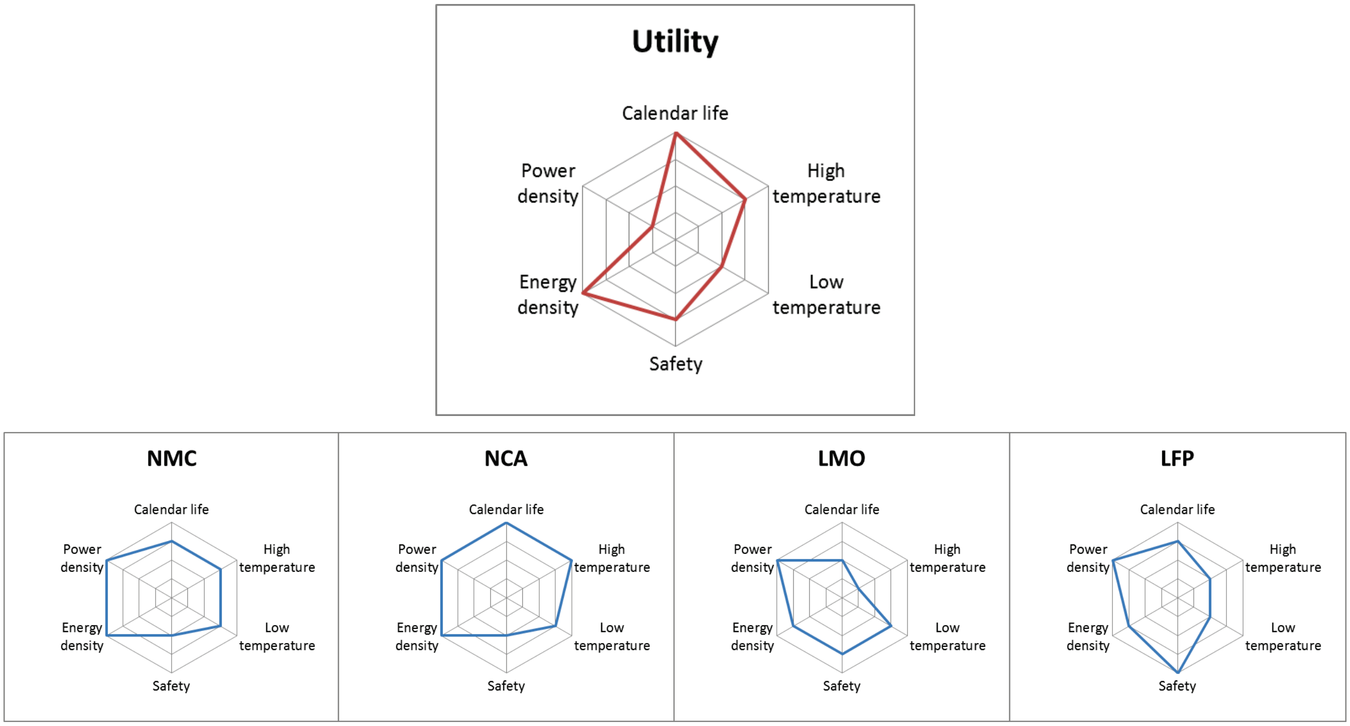

Figure 8. Utility application needs compared to Li-ion technology characteristics

NCA technology provides the closest match, driven by the calendar life and energy density requirements. NMC could also be a good choice, if the calendar life can meet the utility needs. In this case Southern Company opted for NCA. Southern Company worked with a local provider who sourced the various components and integrated the system, shown in Figure 9. The pictured system provides 2 hours of run time at 7 kW and includes a 5 kW inverter to power ac loads, with the remaining 2 kW powering dc loads at 125 V. All equipment is contained in a cabinet with a footprint of approximately 9.5 ft^2 (0.9 m^2).

At a recent presentation of this solution to the IEEE Stationary Battery Committee[7] it was stated that in addition to space savings, this design eliminates the need for large battery rooms, fuse panels, distribution panels, spill containment, safety showers, large exhaust fans and HVAC units.

Figure 9: Compact Power Center (7 kW for 2 hours)
Courtesy: Southern Company

Standards for Li-ion Batteries

One speed bump on the road to increasing deployments of Li-ion batteries in standby applications has been in the area of standards. For several years battery manufacturers had to test larger Li-ion products using generic standards aimed at the portable battery industry, but now the situation is steadily improving. The telecom industry has been leading in the generation of standards specific to Li-ion, particularly with Telcordia GR-3150[8], now in its third edition. For other applications UL has published UL 1973[9] and also UL 1778[10], specific to UPS applications. IEC has one document covering Li-ion batteries in industrial applications, IEC 62620:2014[11], and is expected to release IEC 62619[12], specific to safety, later in 2016. It is crucial for both users and suppliers that there are adequate standards addressing application-relevant criteria, particularly in the area of battery system safety.

IEEE Std 1679-2010[13] can provide guidance on the adoption of new technologies, as discussed in a recent Battcon paper[14]. In addition, the IEEE Stationary Battery Committee has been working on a subsidiary document (to become IEEE Std 1679.1) that will provide guidance on the application of IEEE Std 1679 specifically for lithium-based batteries.

Conclusion

Li-ion technology can offer substantial benefits in certain standby applications. It is important that prospective users understand both the proper application of this technology and the differences between the various chemistries that make up the Li-ion family. The solutions presented in this paper, and the chemistries selected, are specific to the defined application needs, and the solutions may differ as those needs change. But the conclusion remains the same: there is no single Li-ion chemistry that provides an optimum solution for all standby applications.

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