THE EMERGENCE OF LITHIUM-ION BATTERIES WITHIN THE DATA CENTER

A Vertiv Application Report

Introduction

A battery exists to store a specific amount of energy and then release it at the appropriate time, whether that is to provide a working flashlight while changing the tire on a dark road, or when you require an effective bridge to an auxiliary power source.

Many critical facility professionals have been underwhelmed by how their batteries have inconsistently performed. When asked, "Is there a need for an improved energy storage solution for your the data center infrastructure?" owners, users and managers invariably respond … YES.

For the critical data center professional, traditional lead-acid batteries paired with uninterruptible power systems have been the 'go to' source for providing brief ride-through time. Most of these same operators have witnessed the drawbacks to the lead-acid solution at one point or another.

One alternative is to utilize lithium-ion batteries. This paper examines that option and shares a real-world perspective to help data center designers decide if this technology is viable within their data center.

Vertiv has long been a leader in powering data centers with uninterruptible power systems, power distribution units, transfer switches and expert service. Since 1981 we have been monitoring, managing and servicing batteries as part of our power portfolio. It's our goal to use that vantage point and to share knowledge on important energy storage solutions such as batteries and how they behave.

Background

If you remember your early science class, the teacher introduced how batteries work by using simple chemical reactions involving a cathode, anode and an electrolyte.

Over the years, many chemicals have been explored, tested and used to power countless items. Breakthroughs over the years have occurred, from the basic lead-acid battery invented back in 1859 (1), to the lead-acid gel battery in 1934 (2), and to the more recent valve-regulated lead-acid battery (sealed) in 1957. We can also add the introduction of newer alkaline and nickel-based chemistries to see the impressive progress material scientists have achieved in battery innovation and performance.

Today, the progress continues with lithium-ion batteries (LIB). The element Li was discovered around 1818. But for all practical purposes, the LIB had its origins in the early 1970s from the work of physicist John Goodenough and chemist Stan Whittingham (3). We can attribute the commercial success of LIB to Sony in 1991, when they introduced a revolutionary new handheld video recorder which used this type of battery.

So began the exponential growth of lithium-ion batteries. Today, everyone enjoys the benefits offered by this battery which enabled our electronics to become smaller, operate longer and be more powerful. Yet, there have been a few cases when safety has taken center stage.

While data centers and handheld electronics both share in demading more power, smaller battery space, longer run times, safe operation, and a justifiable price point, we need to recognize that the batteries supporting consumer electronics are not to be confused with those used in data centers.

Which brings us to the questions: Can they effectively power a critical infrastructure? Let's dig a little deeper.

The Problem with Traditional Batteries

Experienced users know that traditional lead-acid batteries are often considered the 'weak link' in their data center's power chain. With strings and strings of batteries required to support a modern facility, it might feel as if a possible failure is lurking at any time. These batteries tend to be high maintenance, heavy, and in need of frequent replacement. Innovations in monitoring, management, and service have helped to alleviate some of these pains, but with marginal success and an added cost.

Battery Reliability

According to the Ponemon Research Institute's 2013 study(4) on data center outages, 55% of the unplanned failures were tied to the common lead-acid battery (Fig 1). Follow up studies in 2016 (5) have shown some reduction, but the magnitude is still startling.

Given proper service combined with remote monitoring, Vertiv has demonstrated that these batteries can be effectively managed (with additional investments).

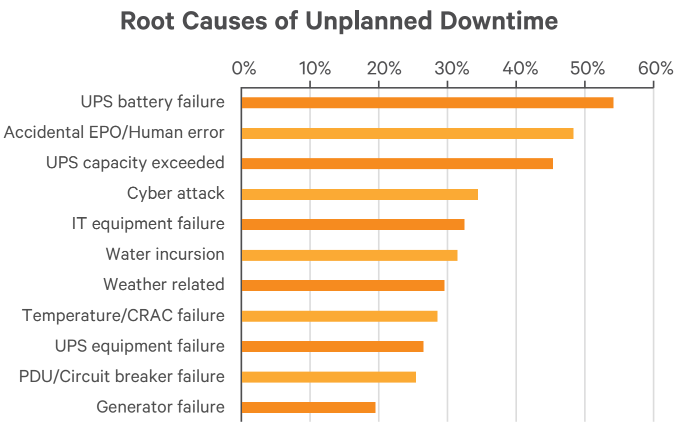


Figure 1: *Over 50% of Unplanned Outages Caused by Battery Failure (2013 Ponemon Study)*

Pain of Replacement

On average, VRLA batteries which support critical applications need to be replaced every 4 to 5 years. With a high quantity deployed, users may feel they face a near perpetual replacement cycle. Each time this occurs, it consumes time and money, and creates additional headaches for the site and its personnel.

So can the right lithium-ion battery provide relief?

Benefits of Lithium-Ion Batteries

From the onset, the attributes of LIB over VRLA have been rather significant.

Longer Life

Many lead-acid battery users have stated, "Why do my VRLA batteries need to be replaced in just 4 to 5 years?" In short, this is symptom of the effective life of the lead-acid battery in critical operations. We can understand why users are excited when they understand that lithium-ion batteries for data centers can achieve life spans of 4 times that of VRLAs (Fig 2). This translates into fewer battery replacement cycles and fewer operational disruptions.

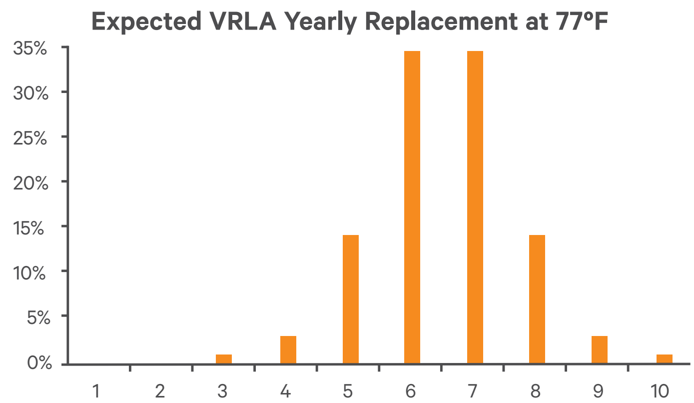


Figure 2: *Trends of VRLA replacements at 77°F*

Less Weight

The comparative power provided in an LIB solution versus a VRLA delivers a significant weight savings of up to 60%. This can reduce the floor-loading thresholds, which in turn can reduce facility construction costs. LIBs also open up the capability to locate batteries in places that have been off limits to heavy VRLA counterparts, such as high-rise buildings. Users may also see lower shipping costs in some situations.

Smaller Size

LIBs have higher energy densities than VRLAs. This fact not only saves weight, but allows the solution to be up to 70% more compact. This means an operation can often avoid big battery room(s). For greenfield sites specifically, space saved can be realigned for better use or omitted from designs to reduce capital construction costs.

Accommodate Higher Temperatures

Depending on the LIB chemistry, batteries can safely operate at higher ambient temperatures without degrading. This can save on cooling costs over VRLA and open up more flexible location options.

Shelf Life

Another benefit that is getting more attention is shelf life. Whereas VRLA batteries require a "top off" charge every six months, LIB batteries can last 18 months with no further attention.

Are All Lithium-Ion Batteries the Same?

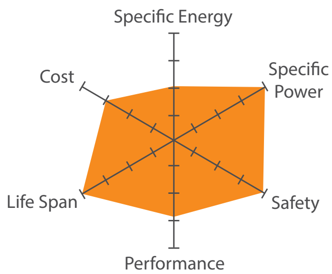
No. In fact there are a host of related family chemistries. The Battery University (6) highlights six common variants along with the chemistry characteristic details of those most applicable for data center use.

CHEMISTRY	LITHIUM COBALT OXIDE	LITHIUM MANGANESE OXIDE	LITHIUM NICKEL MANGANESE	LITHIUM IRON PHOSPHATE	LITHIUM NICKEL COBALT ALUMINUM OXIDE	LITHIUM TITANATE
Short form	Li-cobalt	Li-manganese	NMC	Li-phosphate	Li-aluminum	Li-titanate
Abbreviation	$LiCoC_2$ (LCO)	$LiMn_2O_4$ (LMO)	$LiNiMnCoO_2$ (NMC)	$LiFePo_4$ (LFP)	$LiNiCoAlO_2$ (NCA)	Li_2TiO_3 (LTO)
Comments	High energy, limited power. Market share has stabilized.	High power, less capacity; safer than Li-cobalt; often mixed with NMC to improve performance.	High capacity and high power. Common in consumer devices. Also NCM, CMN, MNC, MCN	Flat discharge voltage, high power low capacity, very safe; elevated self-discharge.	Highest capacity with moderate power. Similar to Li-cobalt.	Long life, fast charge, wide temperature range and safe. Low capacity, expensive

Lithium Iron Phosphate (LFP)

This lithium-ion design leverages iron phosphate. The chemistry tends to provide excellent safety, long life, a relatively modest specific energy, lower voltage patterns, a higher self-discharge, and the ability to operate at higher temperatures. The quick charge feature of LFP batteries can be a noticeable benefit for applications that experience more frequent power failures when compared to slower charging VRLA batteries.

LITHIUM IRON PHOSPHATE: $LiFePO_4$ cathode, graphite anode Short Form: LFP or Li-phosphate, Since 1996	
Voltage, nominal	3.20V, 3.30V
Specific Energy (capacity)	90-120Wh/kg
Charge (C-rate)	1C typical, charges to 3.65V; 3h charge time typical
Discharge (C-rate)	1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage)
Cycle life	1000-2000 (related to depth of discharge, temperature)
Thermal runaway	270°C (518 °F) Very safe battery even if fully charged
Applications	Portable and stationary needing high load currents and endurance
Comments	Very flat voltage discharge curve but low capacity. One of safest Li-ions. Used for special markets. Elevated self-discharge



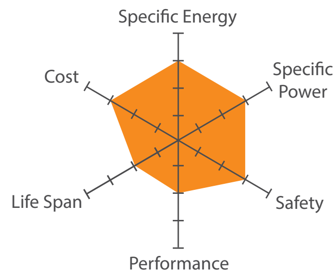
LFP Map

Lithium Manganese Oxide (LMO) and Lithium Nickel Cobalt Manganese (NMC)

Both of these lithium ion based chemistries use manganese. LMO is appropriate for short term power applications while NMC provides greater overall performance and good specific energy behavior.

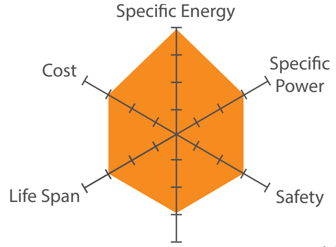
There is also a blend of the two chemistries (LMO/NMC) which works to optimize the advantages of both types. The LMO/NMC is the most common choice found in today's electric vehicles, such as the Nissan Leaf, Chevy Volt, and BMW i8 & i3.

LITHIUM MANGANESE OXIDE: $LiMn_2O_4$ cathode, graphite anode **Short Form**: LMO or Li-manganese (spinel structure), Since 1996	
Voltage, nominal	3.70V (some may be rated 3.80V)
Specific Energy (capacity)	100-150Wh/kg
Charge (C-rate)	0.7-1C typical, 3C maximum, charges to 4.20V (most cells)
Discharge (C-rate)	1C; 10C possible with some cells; 30C pulse (5s); 2.50V cut-off
Cycle life	300-700 (related to depth of discharge, temperature)
Thermal runaway	250°C (482 °F) typical. High charge promotes thermal runaway
Applications	Power tools, medical devices, electric powertrains
Comments	High power but less capacity; safer than Li-cobalt; commonly mixed with NMC to improve performance



LMO Map

LITHIUM NICKEL MANGANESE COBALT OXIDE: $LiNiMnCoO_2$.cathode, graphite anode **Short Form:** NMC (NCM, CMN, MNC, MCN similar with different metal combinations) Since 2008	
Voltage, nominal	3.60V, 3.70V
Specific Energy (capacity)	150-220Wh/kg
Charge (C-rate)	0.7-1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life
Discharge (C-rate)	1C; 2C possible on some cells; 2.50V cut-off
Cycle life	1000-2000 (related to depth of discharge, temperature)
Thermal runaway	210 °C (410 °F) typical. High charge promotes thermal runaway
Applications	E-bikes, medical devices, EVs, Industrial
Comments	Provides High capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing.



NMC Map

The Meaning of Life

Battery life may not excite your dinner guests, but get a few electrochemists together and you're in for an interesting discussion. Soon they will bring up the demarcations around life. You'll hear about design life, warranty life, and end of life. One will explain that design life tends to be the rather utopian yardstick, measured under the most ideal settings. Whereas, the actual/effective life tends to be what drives warranties, which concentrates on the real behavior of battery chemistries given the operating conditions, temperature, cycling, and maintenance practices.

An example is the common VRLA which may have a design life of 10 years but a warranty of just 3 full years and a prorated warranty of 7. At 77°F, in 4 to 5 years the cells begin to fail under normal conditions. For a critical application, it's at this time that replacements should begin. Some VRLA manufacturers are introducing performance improvements with 15 to 20-year life designs. Of course, these designs add substantially to the more standard 10-year VRLA initial cost.

Cycle Counts and Depth of Discharge

Every time a battery is called upon to release some of its stored energy (whether for a second or for five minutes), it discharges and then recharges. This amounts to a cycle. The amount of effective cycles in a battery's life can depend on the depth of those discharges. Visible differences can be witnessed among the various battery chemistries. It should be noted that most batteries are not fully discharged, thus the industry standard uses 80% as a discharge threshold to rate a battery, keeping a so-called reserve.

The battery is considered end of life (EOL) when it reaches 80% of capacity. Generally the battery is oversized by 125% so that at EOL it achieves the required capacity. VRLA hits EOL in year 3 to 5 versus LIB which hits EOL between year 13 to 15. Therefore, LIB is at 93% when VRLA is at 80% EOL (see Fig 3).

It is generally accepted that LIBs provide a higher cycle count than standard VRLAs. As previously noted, exact behavior will vary depending on the four factors. In a paper by Shouzhong Yi (7), he mentions that LFP are showing increased cycle counts on the order of 10x from that of VRLA. Even at deep discharge application (80% DOD or greater), he notes that LFP batteries can serve ten years or more.

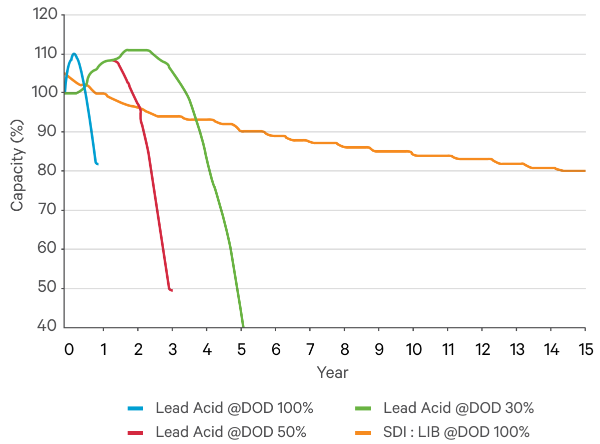


Figure 3: *End of life comparisons by DoD (Depth of Discharge)*

Trust but Verify

Critical operations place a high dependency on energy storage, so it's no wonder battery monitoring is vital. Used correctly, this technology can directly verify performance and initiate proactive service. With lead-acid, this became especially important to improve its spotty performance history. Of course, LIB battery management is equally as important if not more critical. Unlike lead-acid, lithium-ion batteries used with UPSs are manufactured with integrated intelligence that enables management and monitoring. We can obtain cell and cabinet details such as voltage, current, temperature and alarms. It is recommended these systems tie into a system-level solution to expand the visibility and capability of the monitoring. Vertiv has a long history in this practice and can offer an Alber solution to monitor a complete battery environment, as well as provide remote services that ensure 24x7 support whether for lead-acid or LIB.

Safety First

It's true that all energy storage devices require some level of caution. Maybe you have read about a few troubling LIB stories, experienced predominately in several consumer electronic devices. The degree of energy density packed into small devices using certain lithium-ion chemistries provided unique challenges. We should note that with millions of these devices in the market, the statistics did display a relatively low LIB incident rate. Still this issue must be addressed.

Fortunately, high-end commercial applications (as in UPSs) are not faced with the challenges that consumer designs provide. The LIBs for a UPS utilize safer chemistries, bigger operating quarters, more robust packaging materials, and less stressed user environments. All of which open the door for establishing greater safety precautions. In fact, leading LIB manufacturers utilize x-ray imaging to ensure every cell passes quality inspection. Safety fuses, overcharge protection, and hardened material layers are but a few of the built-in safety advances. In short, these designs minimize the chance of thermal runaway. The battery monitoring and management capabilities add to the performance and security.

Today, UL has standard testing and qualification processes in place to verify a safe solution. UL 1973 (cabinet/safety) is required by most electrical inspectors and building insurance carriers in addition to UL 1643 which covers the battery cell.

Is the Price Right?

We can appreciate that our critical facility community is rather pragmatic. They look to initiatives that perform and have a positive ROI. A total cost of ownership evaluation for energy storage should include the initial cost, installation, service/maintenance, replacement expense, shipping and disposal.

Currently, the initial cost of an LIB solution is noticeably higher than that of a standard VRLA. As of this writing, the North American pricing for an LIB is at a premium of approximately 1.75x to that of a comparable VRLA deployment. LIB prices dropped radically earlier in the decade and decreased more modestly over the past 5 years. Though it is unlikely the critical UPS industry will experience the drastic reduction that swept the automotive industry, we should expect moderate price reductions as the technology's deployment rate continues.

What about other operating costs? Though LIBs should not be classified as 'maintenance free', they do carry lower maintenance and service costs than VRLAs. Lithium-ion batteries are considered disposable; but given the relative newness of LIBs, the ecosystem for recycling has not yet developed in North America, though is progressing in some countries. Most expect this recycling gap to narrow, driven initially by the sheer volume in the automotive market. Of interest, the "after-market" for LIB is expected to grow. Many applications that are less demanding than critical data centers are delighted to reuse LIBs taken out of service even after 15 years.

A significant factor in any battery TCO model is the replacement costs. This is where LIBs pickup most of their ROI points, as they can delay the need for more frequent replacements.

Let's Compare

Vertiv conducted a recent battery cost comparison exercise which took into consideration the factors of initial cost, service and maintenance, replacement cost and disposal, using a variety of leading battery manufacturers. We evaluated the batteries based on a 1 MW load (using a 9 minute run time). The exercise helped to demonstrate a real-life energy storage evaluation across battery types.

The findings revealed several important distinctions.

First, the VRLA initial and replacement cost trended in close proximity to one another across each manufacturer. This tends to verify the maturity of this technology, as seen in the similar street pricing between brands. Second, we see the replacement cycles of VRLA compared to the more linear progression of LIB.

We also factored in the current disposal costs of both VRLA and LIB (as seen by the end of life bump).

Finally, the study shows a return on the LIB investment beginning just before and/or after the second VRLA replacement cycle. The analysis did not include a cost of money, nuisance costs around replacements, potential revenue from smaller space or a reliability factor.

9M Initial Runtime at 1000kW Load

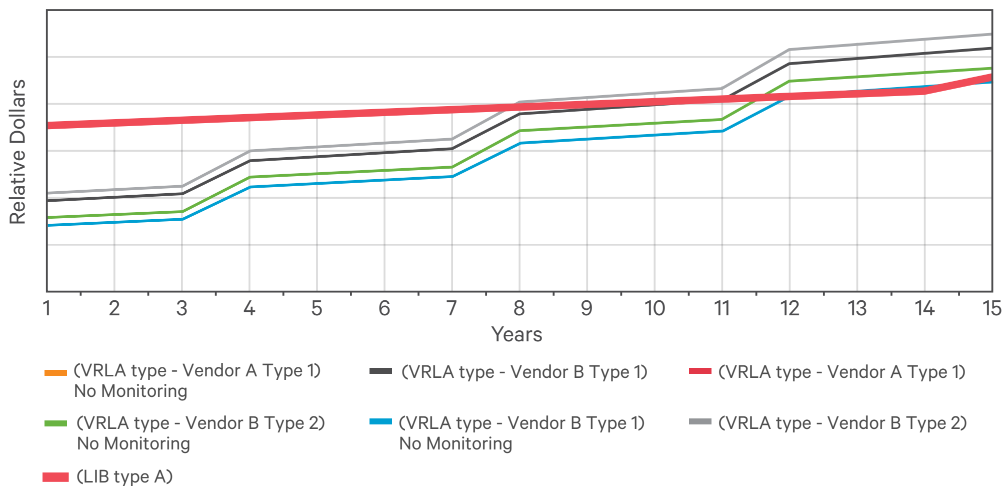


Figure 5: *Models VRLA and LIB over 15 year at 9 minutes of runtime*

Conclusion

After looking at the specifics around LIB and lead-acid energy storage alternatives, we can see the future looks promising for lithium-ion batteries. They are designed to bring extended life, reduced weight, smaller size and greater flexibility to modern data center providers. We are witnessing the beginnings of favorable cost models. The market will continue to monitor if and how lead-acid manufacturers respond.

The movement to LIB will be led by the innovators. How soon they will be mainstreamed will likely depend on the experience of these earlier deployments. Given the significant benefits of lithium-ion batteries over standard solutions, this may well be quicker than expected.

For more information on Lithium-Ion Battery solutions for UPS applications, please visit VertivCo.com.

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(7) Paper: Discussion on Lithium Iron Phosphate Batteries Used for IDCs Compared with VRLA Batteries, Shouzhong Yi, Chief Technical Officer, Shenzhen Center Power Tech Co., Ltd from Battcon 2016 conference.

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