Batteries for Tough, Critical Applications

ALM® Product Line vs. Lead-Acid:
Introduction

Lead-acid batteries have been in service for over a century with broad use across many applications and industries. Over the years, improvements in design, construction, and materials have increased reliability and kept initial costs low. However, size, weight, and low energy density have made them less than ideal in a growing number of applications. Additionally, the performance, service life, and total cost of ownership in frequent and deep cycling applications, even under extreme temperature environments further limits their usefulness and advantages. Lithium-ion battery packs have emerged in recent years as small size, light weight, and high energy density solutions. Lithium-ion batteries are gaining increasing usage in industrial, communications, motive, and military applications over lead-acid batteries. The benefits of lithium-ion technology over lead-acid batteries are being realized in a number of new and emerging applications and in use cases where lead-acid batteries are simply not practical or cost effective. This paper reviews the utility and benefits of NEC Energy Solutions ALM® lithium-ion battery product family versus lead-acid batteries.

Lead-Acid Batteries

A typical 12 V lead-acid battery is constructed using six 2 V nominal (2.10 V to 2.14 V) cells connected in series for a battery pack that is 12.6 V to 12.8 V nominal. There are two basic constructions used today, flooded (wet) and sealed batteries. Each of these battery constructions has a number of product variations that address specific applications and requirements.

Flooded Batteries

Flooded lead-acid batteries have a conventional liquid electrolyte with removable caps so the electrolyte can be monitored and maintained. Standard flooded batteries are low cost and if properly maintained are not overly sensitive to high charging voltages. They must remain in an upright position with valve caps not inverted. This is to insure gas venting, access to regular electrolyte replenishing, and to prevent leakage. Flooded batteries are typically the heaviest lead-acid battery type for a given voltage and capacity.

Sealed Lead-Acid (SLA) Batteries

There are two types of sealed lead-acid batteries. Gelled electrolyte and Absorbed Glass Mat (AGM). These batteries use electrolyte material that does not require regular maintenance and can be oriented in any direction without concern for electrolyte leakage. They are often referred to as Valve Regulated Lead-Acid (VRLA) batteries. They do not vent gas under normal operating conditions, but are constructed to vent retained gas if pressure builds up due to stressful charge or discharge. The major drawback is they cost between 2 or 3 times as much per unit capacity as flooded batteries.

Gelled Electrolyte – The electrolyte is a jelly and so will not leak. Since the electrolyte cannot be diluted, over charging must be avoided. Typical batteries of this type may only last for 2 or 3 years in hot climates, although with good care they can last for 5 years.

Absorbed Glass Mat (AGM) – The electrolyte is held between the plates absorbed in a fine boron-silicate mat. Like gelled electrolyte batteries, they will not leak acid but they can withstand careless treatment and are less sensitive to overcharging.

Advanced Lead-Acid Batteries

Advanced lead-acid usually pertains to various incremental improvements to lead-acid cell construction. These are usually improved battery performance in some dimension such as cycle life or discharge performance. The improvements are realized by controlling the purity of the lead, its mechanical dimensions or thickness, or by introducing specific elements to enhance performance or service life.

Lithium-Ion Batteries

The term lithium-ion refers to a family of chemistries used for secondary or rechargeable cells, which all share a common trait: energy is stored using lithium-ions in the cathode and anode. Energy is stored by the insertion of lithium ions in/out of the electrodes. Lithium-ion cells consist of anode and cathode materials shaped as cylindrical or prismatic cells. Lithium-ion batteries are generally separated into two groups: Lithium metal phosphate (Iron, Magnesium, or others) and lithium metal oxide (Cobalt, Manganese, Nickel, and Aluminum). These materials constitute the cathode chemistry with the anodes made in some cases of carbon with small amounts of silicon. Lithium-ion batteries store the most energy per volume and weight compared to lead-acid or any other chemistry as shown in Figure 1.

Figure 1: Energy Density and Specific Energy

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Lithium iron phosphate (LiFePO₄) cells are the most common type of lithium phosphate cells and have a 3.3 V nominal voltage. Four cells are connected in series to make a battery pack of 13.2 V nominal. Lithium metal oxide-based chemistries have a 3.7 V nominal cell voltage, and hence are more difficult to configure for typical 12 V applications. Lithium-ion battery packs, regardless of cell type used, are lightweight and can be oriented in any direction. There is no issue with electrolyte leakage or outgassing under normal operating conditions.

### Comparing ALM® Lithium-ion and Lead-Acid Batteries

#### Battery Capacity, Amp-hour (Ah)

Battery capacity refers to the amount of charge contained by the battery, and the typical unit of measurement is the Ampere-hour (or Amp-hour, Ah). One Amp-hour equals 1 ampere of current provided for a period of 1 hour. Theoretically, a 20 Ah battery is able to deliver 20 A for 1 hour, however, in practice, the relationship between current and time for a given capacity varies. A normalized metric for this relationship is called C-rate, which describes a current (charge or discharge) relative to a battery’s stated capacity. The C-rate metric allows certain battery specifications to be provided independent of the physical size of the battery. Batteries from coin cell, vehicle batteries, to large grid storage system are described using C-rate.

The realizable capacity of all batteries varies with the C-rate at which a battery is discharged (or charged) relative to its maximum capacity. For example, a 1C rate is the current that discharges the full capacity of a battery in 1 hour. For a battery with a capacity of 10 Ah, this equates to a discharge current of 10 A for 1 hour. A 5C rate would be 50 A for 1/5 hour or 12 minutes, and a C/2 rate would be 5 A for 2 hours. The time to discharge is often referred to as the run time or discharge time.

Batteries are specified by a nameplate capacity (the marketed nominal capacity) for a particular discharge or charge time (or C-rate). Nominal capacity is the total Amp-hours (Ah) available when discharged from 100% State-of-Charge (SOC) to the cut-off voltage for a given battery, usually provided as part of its specification. This is when the battery is considered empty or at 0% capacity.

Lead-acid battery nameplate capacity is typically specified for a 20 hour discharge time (i.e. a C-rate of C/20). Lead-acid battery capacity varies greatly with C-rate. The available capacity decreases as the discharge current increases. The shorter the discharge time is, the smaller the available capacity and energy. This is due to the increasing internal resistance of the cells when the discharge current increases. This is called the Peukert Effect. The Peukert Coefficient is used to calculate how much the capacity varies with discharge current.

Lithium-ion batteries typically have nameplate capacities specified at 1C or C/2 rates, with a capacity that is nearly independent of discharge current. The NEC Energy Solutions ALM® lithium-ion battery product families exhibit less than 10% variation from nominal capacity at high discharge currents or C-rates greater than 1C. This is because the lithium-ion chemistry used in the ALM family of batteries experiences very little internal resistance growth with discharge (or charge) and hence does not experience the Peukert Effect to the extent of lead-acid batteries.

![Figure 3: Capacity vs. Discharge Rate](image)

![Figure 4: Capacity Discharge Run Time](image)

The comparison of the capacity change for a high quality 12 V, 35 Ah lead-acid battery and the NEC Energy Solutions ALM 12V35 lithium-ion battery is shown in Figure 3 and Figure 4. Figure 3 shows the capacity degradation versus C-rate, and Figure 4 shows

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capacity degradation versus run time. The key point is the capacity of the ALM 12V35 is relatively constant across the C-rate, reduced by less than 7% at a very high 6C rate. At the same C-rate the 12V35 lead-acid battery capacity is reduced to less than 50% nameplate capacity. At a modest C/2 rate, the lead-acid battery capacity is reduced to 75% of nameplate capacity. At this discharge rate, the ALM 12V35 retains its full capacity.

**Battery Energy, Watt-hour (Wh) and Power (W)**

Battery energy is calculated by multiplying the discharge power (Watts) by the discharge time (hours). Energy is expressed as a unit of Wh (Watt-hour). Unlike battery capacity measured in Ah, the energy specification accounts for the change in battery voltage over different states-of-charge and C-rate. All batteries are specified by a nameplate energy (marketed as nominal energy). The nominal energy of a battery is the total Watt-hours available when the battery is discharged at a certain discharge current (C-rate) from 100% SOC to the battery cut-off voltage or 0% SOC. For a battery with nominal energy of 20 Watt-hours, this equates to a discharge of 20 watts (W) of power for a one-hour period, or 5 W for four hours, or 100 W for 1/5 hour or 12 minutes. Like capacity, available energy decreases with increasing C-rate.

Lithium-ion battery available energy, like capacity, is almost independent of the discharge rate or time. The comparison of the power performance for a high quality 12 V, 35 Ah lead-acid battery and the NEC Energy Solutions ALM 12V35 lithium-ion battery, in Figure 5 shows the energy versus C-rate and discharge (run) time. The key point is the power discharge of the ALM 12V35 is relatively constant across the C-rate, reduced by less than 10% at a very high 6C rate. At the same C-rate, the 12V35 lead-acid battery is reduced to less than 50% nameplate capacity. At a modest C/2 rate, the lead-acid battery is reduced to 74% of nameplate energy, while the ALM 12V35 retains its full energy.

![Energy Performance vs. Discharge Rate and Time](image)

**Battery Discharging and Depth of Discharge (DOD)**

Depth of Discharge (DOD) is a measure of how deeply a battery is discharged. For example, if a fully charged battery to a 100% state of charge (SOC) is discharged down to 30% SOC, this would be considered a 70% DOD. For conventional lead acid batteries, the cycle life, or number of charge/discharge cycles supported over the life of the battery, are typically very sensitive to the DOD per cycle. For even modest cycling requirements (for example, a few hundred cycles over the life of the battery), the DOD may need to be limited to as little as 30%. There are deep cycle lead acid batteries that are optimized for improved cycle life for DOD up to 80%, but these may be more expensive than conventional lead-acid batteries.

Effective DOD limits are another significant derating factor for determining usable capacity in a battery system. Discharging lead-acid batteries at or beyond their specified DOD dramatically impacts battery life. Depending on the type of battery, cycles to 50% DOD may significantly reduce its service life, requiring replacement sooner than the design life specified in a data sheet. System designers must take into account battery derating associated with their target DOD operation and application requirements.

The ALM family of lithium-ion batteries can be fully and repeatedly discharged to 100% DOD, with minimal impact on battery life. Additionally, the ALMs contain an internal Battery Management System (BMS) that limits over-discharge to prevent damage or abuse of the battery.

**Temperature Effects on Capacity**

All battery technologies are subject to performance or life time degradation due to temperature variations from a nominal 20 – 25 °C condition.

![Energy C(20) Over Temperature](image)
rapidly with usable energy reduced by ~20% at 0 °C and ~60% at -30 °C. The ALM energy decreases at ~ ½ this rate, with only a ~25% reduction at -30 °C in nominal energy.

At a C/2 discharge rate, the lead-acid battery requires a derating of usable capacity, which is described on page 3 and shown in Figure 4. At decreasing temperature as shown in Figure 7 both the ALM and lead-acid battery experience a decrease in capacity and usable energy. However, the lead-acid battery drops faster between 0 °C to -30 °C, with the ALM offering 1.6X to 2.3X more available energy over the same temperatures as shown in Figure 7.

At temperatures above 25 °C the usable capacity and energy is unchanged. However, improvements in capacity versus higher C-rate can occur with increasing temperature. The biggest impact from higher temperatures is on battery service life rather than usable capacity.

Charging Lead-Acid Batteries

Lead-acid batteries require a specific charging sequence to assure a full charge and maximum service life. The method that is typically used is a Constant Current, Constant Voltage (CCCV) charging profile. For a 12 V battery, the charge voltage range is 14.2 V to 15.5 V, with a float voltage (trickle charge) from 13.0 V to 13.2 V applied to keep the battery from discharging. The typical lead acid battery charging profile is shown in Figure 8. The total recharge time for lead-acid batteries is generally greater than 10 hours.

The charging sequence is as follows:

1. Initial capacity of ~70% is reached in bulk charge stage (5 – 8 hours)
2. Remaining ~30% of capacity is reached in the absorption charge stage (7 – 10 hours).

The absorption stage is a required period where the charge voltage is held constant with a timer and the charge current decreases slowly until the battery is effectively charged.

3. Once the lead-acid battery is charged, it requires a float, maintenance, or trickle charge to maintain the SOC above a specified minimum.

This is important as lead-acid batteries have a self-discharge, which varies widely by battery type (i.e. flooded, SLA, advanced lead) and by manufacturer. A typical lead-acid battery has a self-discharge of 2% per month at 20 °C, and 8% per month at 40 °C. This means the battery will require a recharge every 6 months at 20 °C, and every 2 months at 40 °C. Since the service life of a lead-acid battery is dimensioned with every discharge below a specified minimum SOC, it is important that the batteries remain as fully charged as possible to avoid self-discharge induced wear.

Some lead-acid batteries, such as deep cycle types, are constructed to support faster charging routines. While the use of these batteries can speed up the charge time, the complete charge routine is still measured in hours.

Charging ALM Family of Lithium-Ion Batteries

The ALM family of lithium-ion batteries can be charged using lead-acid compatible chargers as described above. In this case, ALMs are a drop-in replacement for equivalent lead-acid batteries. Lead-acid float voltages may be used without impacting the ALM batteries’ float life.
For new designs and applications where simpler or faster charging routines are needed, the ALM family offers significant advantages over lead-acid batteries. Figure 9 shows the general charging scheme that is recommend for ALMs. Due to the inherent low discharge rate and no self-discharge induced wear, no trickle or maintenance charge is required. The shelf life is two years at 25 °C before a recharge is required. Even if the ALM SOC falls to 0%, it can be recharged and not suffer degradation as a result.

The ALM family, by model number, has the following charge rates for 0% to 100% SOC.

- 3C rate (20 min) for the ALM 12V3S
- 6C rate (10 min) for the ALM 12V35i HP
- 4C rate (15 min) for ALM 12V7s
- 9C rate (6.7 min) for ALM 12V7s HP

ALM 12V7s Data Sheet: https://www.neces.com/assets/12V7s_datasheet.pdf
ALM 12V35 Data Sheet: https://www.neces.com/assets/NEC_12V35_datasheet.pdf

ALM batteries can be charged at 30 – 60X faster rate than equivalent lead-acid batteries. This is a major benefit for cycling applications where equipment availability is critical, such as recovery from a power outage. For off-grid systems, this means significantly less fuel consumption for fuel based generators/chargers to charge up a battery array. Up to 90% fuel reduction can be realized using the ALMs fast charging capabilities versus slower charging lead-acid batteries.

Charging Temperature Compensation

Lead-acid battery chargers must adjust the charge voltage with changes in ambient temperature. As the temperature rises above 20 °C, the charge voltage must decrease. As the temperature falls below 20 °C the charge voltage must increase. In addition, the charge rate must be adjusted to a lower charging rate and current when the temperature drops below ~20 °C. The amount of voltage and charge rate adjustments varies depending on the manufacture and type of lead-acid battery. Most lead-acid battery chargers have built-in adjustments to automatically compensate the voltage and charge rate based on temperature. Figure 10 is a typical curve.

For ALM batteries connected to lead-acid battery chargers, the voltage adjustment compensation versus temperature is not required and should be disabled. Chargers should contain instructions on how to disable the temperature compensation.

The ALM charge rate must be reduced as the temperature decreases below 20 °C. Typical values for the ALM 12V3S are shown in Table 1 to illustrate the rate versus temperature. Charging rate versus temperature must be considered carefully for outdoor applications.

Battery Life

Battery End of Life (EOL) is determined by the capacity reduction from the Beginning of Life (BOL) capacity to a specified level where an acute battery failure (unable to hold a charge and deliver energy to a load) is more likely. For lead-acid batteries, EOL is usually specified as 80% of BOL capacity. For lithium-ion batteries, the EOL capacity is usually lower, such as 60% of BOL capacity, although application requirements are more likely to determine how much capacity loss is acceptable before replacement is desired. While the term service life as used by battery suppliers can be misleading, here it is used to denote the actual useful life of a battery in a given application scenario. The two major factors in determining service life are calendar (or float) life and cycle life.
Calendar and Float Life

Calendar life is the expected battery life duration based on time aging effects, whether in active use or in storage. Float life is the expected lifetime of a battery when used in a float charge application. Calendar life is often synonymous with float life, which assumes constant float voltage use of a battery. Calendar and float life are due to aging losses induced by the electrochemical reactions that happen when a battery is sitting idle in a non-exercised state either on a shelf or energized and connected to a system. These lifetimes are expressed in units of time, usually years. For example, a lead-acid battery calendar life is defined as the time to capacity fade to 80% BOL capacity. The estimated float life for three different lead-acid batteries and a lithium-ion battery, at 25 °C, are shown in Figure 11. The differences for the lead-acid batteries are due to the battery type, quality, and manufacturer.

Cycle Life

Cycle life is the expected battery life duration based on charge/discharge cycling effects, independent of time aging; expressed in the number of cycles. The life time is the number of cycles a battery can perform before it fails to meet certain performance criteria, usually capacity fade. For most lead-acid batteries, end of life is when the capacity falls below 80% BOL.

Cycle Life depends on many factors, including: temperature, depth of discharge (DOD) per cycle, average and/or partial State-of-charge (pSOC), and charge and discharge rate.

These parameters are not always specified on lead-acid battery datasheets. Specifically, the charge and discharge rates and depth of discharge are not always mentioned in relation to cycle life, despite their strong effect on it. Lead-acid batteries, in general, have much lower cycle life performance than other battery technologies, even for lead-acid batteries that are optimized for cycle life performance. For example, a cycle life optimized lead-acid battery operated at 30% DOD has a ~3X greater cycle life than at 80% DOD. For deep cycling applications like off or weak grid back up that often demand energy to greater than 50% DOD, a system designer is faced with either oversized the battery system, or planning for frequent replacement of batteries due to reduced lifetime.

The ALM lithium-ion batteries have up to 100X greater cycle life as compared to typical lead-acid batteries. The ALM cycle life is specified at continuous 1C discharge and 1C charge rate cycles, with a 100% depth of discharge DOD. Lead-acid batteries cannot survive very long under the rigors of such deep, fast, and frequent cycling. The cycle life for the ALM shown below is based upon actual cell cycling data collect by NEC Energy Solutions over many years. The results at 25 °C are as follows.

> 8,000 cycles to 80% of BOL capacity
> 14,000 cycles to 70% of BOL capacity
> 20,000 cycles to 60% of BOL capacity

Unlike lead-acid batteries that usually become nonfunctional below 80% BOL capacity, the ALM lithium-ion battery will continue to operate down to a 60% BOL capacity extending its useful life.

Cycle Life vs. partial SOC

Some applications require partial State-of-Charge (pSOC) operation – i.e. charging to less than 100% SOC. These often occur during partial cycling over different SOC conditions and unsteady charge/discharge cycles that can occur in unstable grid applications or PV solar installations. For lead-acid batteries, pSOC operations negatively impact cycle life and reduce the overall service life. This is due to the lead-acid batteries not operated within their optimum SOC and depth of discharge to minimize electrode corrosion/sulfation. These effects greatly reduce battery life, requiring frequent replacement.

The ALM family of batteries uses lithium Nanophosphat® (LiFePO₄) cells, which has an extremely high cycle life. However, performance across different delta SOC cycles and partial SOC applications still yields very high cycle life as shown in Figure 12.
Temperature Effects on Calendar and Cycle life

All battery technologies are subject to performance or life time degradation due to temperature variations from a nominal 20 - 25 °C environment.

At high temperatures, calendar, float, and cycle life are impacted. The calendar/float life for ALM and lead-acid batteries are cut in half if the average temperature is increased from 25 °C to 35 °C. Under this condition, a lead-acid battery with an expected calendar life of 10 years (25 °C) will be reduced to 5 years (35 °C). The calendar life is cut in half again for every additional 10 °C increase.

The ALM family of lithium-ion batteries has a calendar life that exceeds 20 years (at 25 °C) to 80% BOL capacity Figure 13, and can extend useful operation to down to 60% BOL. The ALM calendar life is reduced by high temperatures at a similar rate to lead-acid batteries, but with 2X – 3X longer calendar life, greater than 10 years can be realized at 35 °C, or longer if the BOL capacity is extended to 60%.

For cycle life, the ALM maintains at major advantage over lead-acid batteries, even as both are reduced with temperature. The key factors on cycle life, in addition to temperature, are the discharge rate, depth of discharge (DOD), and frequency of the cycling.

There are high quality lead-acid batteries optimized for cycling applications. For example, a high quality battery of this type can provide good cycle life even at 80% DOD. If it is cycled once a day, every day at 25 °C, it is specified to provide 1,200 cycles and survive ~3.3 years. If the temperature is increased to 40 °C the battery has cycle life derating of 0.62. This means the cycle life is reduced by 1,200 x 0.62 = 744 cycles. Under a once a day every day cycle application battery, the battery is expected to survive ~2.0 years in this high temperature application.

The curves in Figure 13 and 14 show the cycle life performance of ALM batteries. The ALM is cycle data is at 100% DOD for 1, 2, and 3 cycles per day. These are plotted at 25 °C and 40 °C. The cycle life expectations are 5X – 10X higher than the cycle optimized lead-acid battery. If a typical lead-acid battery were used, the ALM battery would exceed the typical lead-acid battery cycle life by an even greater margin.

Service Life

Service life is the period of time a battery is expected to meet the energy or power requirements for a specific application, which includes calendar, float, and cycle life effects.

Lead-acid batteries are optimized for either calendar/float or cycling applications (i.e. cycle life). Lead-acid battery data sheets often describe design life to set expectations for how long a battery will last, but it is not a specification. In many cases, it is not the batteries’ expected service life.

Calendar life for all batteries is affected by operating temperature, decreasing with increasing temperature.

ALM calendar life exceeds 20 years (at 25 °C) to 80% BOL capacity, and will remain useable to less than 70% BOL capacity. Even with a daily 100% charge/discharge cycle, the ALM service life extends beyond 20 years at 25 °C, and for 10 years with 3 daily 100% charge/discharge cycles, as shown in Figure 13.

In ‘float service’ applications, ALMs have 2X longer service life than typical lead-acid batteries. Even at high temperatures, ALMs have twice the service life. In cycling applications, ALM performance is vastly superior with 5 – 100X the cycle life versus cycle optimized lead-acid batteries, even over temperature extremes.
The ALM battery service life may in many cases equal the lifetime of supported products. This can result in significant Total Cost of Ownership (TCO) improvements and advantages, particularly in remote, hard-to-reach and expensive-to-service applications and locations.

**Specific Energy and Energy Density**

To qualify the weight and space efficiency of various battery chemistries and technologies, metrics for Specific Energy (Gravimetric Energy Density) Wh/kg and Energy Density (Volumetric Energy Density) Wh/l are used. Figure 1 on page 2 shows the relative ranges for the most widely used chemistries today.

Lead-acid batteries by the nature of their chemistry and construction are one of the largest and heaviest energy storage solutions available. Lithium-ion batteries are one of the smallest and lightest energy storage solutions, with the benefit of high energy and power capabilities.

Table 2 shows a comparison of the ALM 12V7 and ALM 12V35 batteries to lead-acid batteries of the same nominal ratings. The specific energy is greater than 3x higher than lead-acid batteries as benchmarked to a 2C rate. Even at C/20 rate, they are 1.7 times higher.

The ALM family has 30 – 63% more usable energy compared to an equivalent lead-acid battery in similar footprint.

<table>
<thead>
<tr>
<th>Battery</th>
<th>Energy at 2C, 25°C (Wh)</th>
<th>Weight (kg)</th>
<th>Specific Energy (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALM 12V7</td>
<td>66.0</td>
<td>9.9</td>
<td>72</td>
</tr>
<tr>
<td>Lead Acid 12V7</td>
<td>50.4</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>ALM Benefit</td>
<td>&gt; 40%</td>
<td>&lt;5%</td>
<td>3.6X higher</td>
</tr>
<tr>
<td>ALM 12V35</td>
<td>434.0</td>
<td>5.3</td>
<td>69</td>
</tr>
<tr>
<td>Lead Acid 12V35</td>
<td>265.0</td>
<td>1.5</td>
<td>23</td>
</tr>
<tr>
<td>ALM Benefit</td>
<td>&gt; 63%</td>
<td>&lt;45%</td>
<td>3.0X higher</td>
</tr>
</tbody>
</table>

Because of the low weight, small size, and high energy the ALM’s are an excellent choice for:

- Pole or wall mounted systems
- Roof-mounted or other restricted weight environments
- Backup power in raised floor data centers
- Restricted space cabinets

**Battery Maintenance and Monitoring: Lithium-ion vs. Lead-Acid**

Lead-acid batteries require external monitoring for SOC and State-of-Health (SOH) in order to monitor their capacity and energy capabilities and as part of the required terms and conditions of a product warranty. Lead-acid battery warranties and terms vary by vendor, product line, and region. They are usually 1 – 3 years full-replacement, some with prorated capacity terms for a longer period, sometime up to 10 years. The terms require strict operating conditions and complicated maintenance and reporting to validate the warranty during the prorated period. The warranties are usually invalid if these are not followed.

The SOC is indicated by terminal voltage, but this is often not accurate across the batteries’ life. Sometimes the monitors are built into the power and charging systems. They generally measure the terminal voltage, charge/discharge, and other parameters. Many independent monitoring systems aimed at lead-acid battery installations are available and consists of sensors, communications and software in some cases. These tend to be used in mission critical systems such as data centers and telecom sites. The system can be complex to set-up and use, and expensive to deploy. However, most lead-acid batteries do not provide any built in protections against external abuse conditions, such as overcharging and short circuit. Protection and safety countermeasures against abuse are up to the battery user and system designer.
The ALM family of batteries, the ALM 12V7s and ALM 12V35, includes EverSafe™ protection technology as part of the Battery Management System (BMS) in each battery, as shown in Figure 15 and 16. This technology delivers fully redundant protection from internal failures or external abuse. It provides system-level protections for battery strings and power system operation, with automatic adjustments and recovery from system level faults or abusive application.

Figure 15: ALM 12V35 Construction

Figure 16: BMS and Intelligent Series Block Diagram

The ALM 12V35 intelligent i-Series of lithium-ion batteries are solutions that provide integrated CAN bus or SMBus communications that provide remote monitoring and control of critical battery status, usage tracking, SOC, run time to empty, and other parameters. The SOC and SOH information, along with other important battery parameters and status are readily available, Figure 16.

Determining the SOC for non i-Series ALMs requires external monitoring circuits since terminal voltage does not reliably indicate SOC or SOH.

Use Case Limitations, Total Cost of Ownership (TCO):
ALM 12V35 vs. Lead-Acid

Lead-acid battery performance and costs vary considerably based on:

- Battery optimizations (general purpose, cycling service, float service, pSOC)
- Battery type (SLA, VRLA, pure lead, thin-plate lead, others)
- Region (North America, Europe, Asia, others)
- Quality (proven vendors versus emerging suppliers)
- Volumes / contracts / warranty terms and conditions
- Pricing for similarly sized batteries can vary 2-3X based on these parameters

Lithium-ion battery first costs are usually higher than most lead-acid batteries. However, in a number of applications, the ALM lithium-ion battery provide significant system level cost and performance benefits:

- Higher system capacity, usable energy, and power performance
- Less system oversizing; fewer ALMs needed than equivalent lead-acid batteries
- Significantly longer service life, fewer and less frequent battery replacement, if any, and associated servicing costs
- Faster charge rates enable more efficient system operations, less generator fuel consumption (lower OPEX)
Example: Usable Capacity

A specific example will be helpful for comparing a quality lead-acid battery and the ALM lithium-ion family. Figure 17 shows an example of the effect of cycling, DOD, and discharge rate. Derating factors depend on target discharge time, number of cycles, and temperature. The use case shown in Figure 17 is a **2-hour backup with 500 power cycles over 10 years in a 25 °C temperature controlled environment.**

The lead-acid battery shown in this example is a high quality lead-acid battery\(^2\) for balanced float and cycle life.

The following derating factors apply:

- **Float life capacity derating** is the amount of capacity (Ah) lost over the 10 year calendar life of the battery assuming float service only (no cycle life reduction included).
- **C/2 Rate capacity derating** is the reduction in specified capacity (versus nameplate) due to a targeted C/2 discharge rate (versus C/20 typically suggested for lead-acid batteries).
- **Safe DOD limit** is the recommended limit on DOD before battery service life is significantly impacted. For lead-acid battery the limit is a function of the number of cycles. The maximum DOD is 70% for a cycle life of 500 cycles.

*Figure 17* shows capacity derating from 70% to 25% nameplate capacity, a significant reduction considering the battery is used in a temperature controlled environment and only cycles on average 20 times per year. This is a common challenge where a system designer needs to oversize the nameplate capacity by 3X – 4X to meet system energy requirements. For example, a system that requires 30 Ah of capacity at the end of 10 years requires three 12 V, 40Ah lead acid batteries, for an overall 120Ah beginning of life capacity, to ensure a full 30 Ah capacity after derating. A single 120 Ah battery could be used. For the ALM 12V35 the calendar life derating is 12% for 10 years, thus a single battery can ensure the 30 Ah capacity over the 10yr life span. The ALM provides greater than 3.5X more capacity on average than the 12 V, 40Ah lead-acid battery, eliminating capacity oversizing, extra weight, volume, and cost.

Example: Use Case, TCO Analysis

Another example illustrates a comparison in total cost of ownership. Consider the following application requirements:

- **System Energy Requirement:**
  - 12 V nominal, with 300 Wh across the life of the battery up to End of Life (EOL)
  - 5-hour discharge (or run time) and charge time.
  - 2 cycles per day, 25 °C controlled temperature
  - 10-year service life
  - Battery Selection: Cycling & partial SOC (pSOC) optimized 12 V, 40 Ah lead-acid battery\(^3\) versus ALM 12V35 lithium-ion battery

**Analysis**

1.) **Number cycles expected over 10 years.**
   - 2 cycles/day x 365 days/year = 730 cycles/year x 10 years = 7,300 cycles

2.) **Beginning of Life (BOL) energy to meet the EOL energy requirement. Apply manufacturer derating factors.**
   - EOL system energy = 300 Wh

   - 12 V, 40 Ah\(^3\) = BOL energy 480 Wh => Derating Factors (Table 3) = 68 Wh to 137 Wh based on % DOD limits
     a.) C/5 or 5 hour runtime derating comes from manufacturers Discharge Tables @ 25 °C\(^3\). The End of Discharge Voltage (EODV) for a 5 hour discharge is 1.75 V. The power at this cell voltage is used.
     b.) DOD level impacts the usable energy, service life, and number of batteries to meet the EOL system energy of 300 Wh.
     c.) EOL Energy is at 80% BOL energy. At this point, the battery will be at the end of its useful life and requires replacement.
3.) **Service Life.**

- **12 V, 40 Ah** ⇒ **Dependent on the DOD limit for 2 cycles/day = 1.8 – 5.0 year Service Life. See Table 3**
  The service life is strongly dependent on the DOD level and cycles per day. The larger the DOD and number of cycles the shorter the service life. The manufacturer provides partial SOC, % DOD curves against cycles per day and useful life. The curves are for conditions where the number of pSOC cycles and % DOD are known, which is the case for this example.

- **ALM 12V35** ⇒ **No DOD limits for 2 cycles/day = 14 year Service Life. See Table 3**
  Effects of DOD on service life are minimal under the system conditions. The number of cycles/day impacts service life, see Figure 13.

<table>
<thead>
<tr>
<th>Battery</th>
<th>BOL Energy (Wh)</th>
<th>DOD Limit</th>
<th>C/5 Rate Energy</th>
<th>EOL Energy</th>
<th>Usable Energy %</th>
<th>EOL Energy (Wh)</th>
<th>Number Batteries BOL</th>
<th>System Energy EOL (Wh)</th>
<th>Service Life (years)</th>
<th>Cycle Life</th>
<th>Total Number Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALM12V35</td>
<td>412</td>
<td>100%</td>
<td>100%</td>
<td>70%</td>
<td>70%</td>
<td>323</td>
<td>1</td>
<td>323</td>
<td>14</td>
<td>&gt;10,300</td>
<td>1</td>
</tr>
</tbody>
</table>

4.) **Number of batteries needed at BOL and total number of batteries over 10 year service life.**

- **12 V, 40 Ah** ⇒ The number of batteries BOL is depended on the % DOD. This is because the overall useable energy follows the size of the DOD limit. The service life increases as the DOD limit is decreased. These opposing factors create a challenge to the overall system sizing and number of batteries put into service. In this example, the optimum energy sizing is at a 30% DOD and matches closely to the EOL energy requirement, while using the fewest number of batteries.

It should be noted that larger capacity batteries could be used in place of the 12 V, 40 Ah. The same DOD, C/5 rate, and EOL derating factors apply. The number of cycles and service life remain the same.

<table>
<thead>
<tr>
<th>Battery</th>
<th>BOL Energy (Wh)</th>
<th>DOD Limit</th>
<th>C/5 Rate Energy</th>
<th>EOL Energy</th>
<th>Usable Energy %</th>
<th>EOL Energy (Wh)</th>
<th>Number Batteries BOL</th>
<th>System Energy EOL (Wh)</th>
<th>Service Life (years)</th>
<th>Cycle Life</th>
<th>Total Number Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALM12V35</td>
<td>462</td>
<td>100%</td>
<td>100%</td>
<td>70%</td>
<td>70%</td>
<td>323</td>
<td>1</td>
<td>323</td>
<td>14</td>
<td>&gt;10,300</td>
<td>1</td>
</tr>
</tbody>
</table>

- **At 20% DOD,** a single 12 V, 210 Ah battery can be used. Using the derating factors in Table 4 the EOL estimate is 363 Wh. This system requires 2 batteries over the 10 year service life.

- **At 30% DOD,** a single 12 V, 170 Ah battery can be used. Using the derating factors in Table 4 the EOL estimate is 470 Wh, and is 57% oversized to the EOL requirement. This system requires 4 batteries over the 10 year service life.

- **At 40% DOD,** a single 12 V, 100 Ah battery can be used. Using the derating factors in Table 4 the EOL estimate is 361 Wh. This system requires 5 batteries over the 10 year service life

- **ALM 12V35** ⇒ **Provides its full 100% capacity and only one battery is needed at BOL, and to meet the 300 Wh EOL energy requirement over a 10 year period. This is because the ALM 12V35 (LiFePO4) cells and pack design are optimized for high cycling applications and can operate at 100% DOD with no C/5 rate penalty.**
5.) **Total Cost of Ownership (TCO) over 10 year service life.**

- 10 – 15, 12 V 40 Ah lead-acid batteries are needed in this system versus a single ALM 12V35, adding cost.
- Extra costs are incurred in replacing lead-acid batteries.
- Extra costs from a battery monitoring system and/or manual maintenance of lead-acid batteries.
- Increased space and weight associated with 3 - 5 lead-acid versus a single ALM 12V35
- Increased space, weight, and cost associated with 100 – 210 Ah capacity lead acid batteries.

The ALM lithium-ion batteries are usually higher initial cost than a 12 V lead-acid battery of the same nameplate rating. However, based on usable energy, lead-acid battery derating factors and service life costs, the total cost of ownership of lithium-ion batteries can be up to 50% lower than lead-acid batteries.

**Summary**

- Lead-Acid batteries are the long-standing standard in most energy storage and backup power applications.
- ALM family of lithium-ion batteries offers significant advantages versus lead-acid in these applications.
  - Greater usable capacity and energy
  - Higher power delivery
  - Significantly longer service life, in both float and especially cycling applications
  - Half the weight and better energy density
  - Built-in intelligence and monitoring
- ALM Total Cost of Ownership (TCO) may be much lower than lead-acid batteries, though ALM first cost may be higher.
  - ALM service will often match the supported end application product life
  - Strength of TCO value proposition varies by application and customer

**NEC Energy Solutions, ALM Product Family**

NEC Energy Solutions’ ALM family of batteries, ALM 12V7s and ALM 12V35 include EverSafe™ battery protection technology that provides fully redundant protection from internal failures or external abuse. It provides system-level protections for battery strings and power system operation, with automatic adjustments and recovery from system level faults or abusive application.

This starts inside with redundant temperature sensors and voltage measurements that monitor cell groups. Next voltage, current, and temperature sensor monitors are employed at the battery level for an additional level of safety. When a fault condition is detected power electronics (FETs as eFuse) disconnect charging or discharging of the battery for even further protection. As an extra layer, redundant FETs are used in the charging path. No processor or software is used in cell management or protection circuits.

ALM Family: Specific Layers of Protection

- Fast response to direct short-circuits (e-fuse).
- Automatic balancing of batteries at different SOC in series and parallel strings.
- Easy recovery from fault conditions.
- Fast retry and reconnect from short circuits and other protection conditions.
- Voltage present on terminals for diagnostic purposes even when in voltage protection modes
- Pre-charger circuit allows charging and recovery from under-voltage protection event, including smart chargers.
The ALM12V35 is available in intelligent i-Series with integrated CAN bus or SMBus communications that provide remote monitoring and control of critical battery status, usage tracking, SOC, run time to empty, and other parameters. Communications may be enabled even if the battery is disabled due to protection events.

NEC Energy Solutions ALM family of lithium-ion batteries are designed, manufactured, and tested to ensure international product safety conformity, as well as, application specific certifications.

NEC Energy Solutions ALM products are designed and tested to IEC 62133, UN 38.3, and UL 1973 results in robust products that meet transportation and safety requirements. Proof of certification is available upon request.

NEC Energy Solutions provides a five-year materials and workmanship warranty for its ALM product family. Visit www.neces.com for the latest information and data sheets.

References

1. Peukert’s law, presented by the German scientist W. Peukert in 1897, expresses the capacity of a battery in terms of the rate at which it is discharged.

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