POWERING HEALTH:
BATTERIES & BATTERY MANAGEMENT

Batteries provide backup power during gaps in electricity generation. They are critical for some energy systems but are expensive and may require maintenance or replacement.

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POWERING HEALTH

This document is provided as part of USAID's Powering Health toolkit. Health-care facilities require electricity to maintain perishable supplies and power life-saving technologies. Energy is essential for preventing child and maternal deaths, controlling the HIV/AIDS epidemic, and combating infectious diseases and pandemics.

Reliable electricity can mean life or death for patients in developing country health-care facilities. However, many of these facilities have little or no access to reliable electricity. USAID supports partner countries in understanding the energy needs of their health-care facilities over the long term. This challenge requires local capacity for careful planning, a commitment to maintenance, and dedicated funding.

USAID uses its experience at the nexus of the health and energy sectors to help international development practitioners and health-care administrators design programs that meet the energy needs of health-care facilities. By applying international best practices and lessons learned, stakeholders can help ensure that health-care facilities are able to power standard appliances, such as lights, life-saving equipment, blood and medicine refrigerators, ventilators, laboratory diagnostic tools, and technology that monitors patients' vital signs.

INTRODUCTION

Batteries provide a means to store energy that can be used to power a health facility when the intermittent power supply source is not operational (*e.g.*, when the sun is not shining, the wind is not blowing, or the grid power is off).

For clinics that are on-grid but experience frequent blackouts, batteries can provide backup power to critical loads for several hours (usually between 4 and 24 hours) when primary power is unavailable. For off-grid clinics, batteries are an essential part of a wind or solar energy system. To ensure that energy is available for periods of low/no sunlight or wind, a properly sized battery bank must be connected.

Several factors can lead to battery failure, including lack of routine maintenance, insufficient charging, and excessively deep discharge. The lifespan of batteries can range from 1 to 25 years depending on their design and construction. Long-life batteries are specialized pieces of equipment, and operators should expect them to be more expensive and more difficult to find than short-life batteries. Batteries often need to be replaced before the end of their design life either due to abuse or normal wear and tear. As a result, batteries generally need to be replaced before other system components (*e.g.*, solar panels or system electronics). Thus, if there is insufficient focus on proper battery use and maintenance, and if funds are not available to replace batteries when they fail, the sustainability of off-grid energy systems will be severely compromised.

This document guides toolkit users through basic battery concepts, chemistries, and metrics that donors, program managers, and facility operators should understand before procuring a renewable energy system.

SELECTING A BATTERY

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There are many battery specifications that must be considered when selecting the correct battery for an energy system.

Since batteries are an essential component of a wide variety of products and services (*e.g.*, consumer electronics, transportation, telecommunications), a multitude of battery types and designs exist. Furthermore, battery design is constantly evolving, driven by the ever-increasing demands of electric vehicles, handheld electronics, and the need for grid stability. When selecting a battery, it is necessary to be familiar with common battery performance metrics. While lead-acid batteries are the most ubiquitous battery type in use for backup power applications, the considerations listed here can be used to evaluate and compare the suitability of any type of battery, including lithium-ion and nickel metal hydride.

IMPORTANT CONSIDERATIONS

BATTERY LIFESPAN

The lifespan of a battery is important because it dictates when a battery should be replaced to maintain expected energy system performance. The life of a battery is typically described in two ways: calendar life and charge and discharge cycles. One cycle is a complete discharge and recharge. A battery's calendar life is the longest a battery will last if it is never cycled, and each cycle that the battery experiences will reduce battery life by a miniscule amount. The number of cycles a battery can endure is highly dependent on the amount of energy discharged for each cycle. The level of discharge is quantified by the depth of discharge (DOD) or the percentage of the battery's stored energy that was removed. The larger the DOD of a cycle, the more damage the battery experiences. For example, a flooded lead-acid battery that is completely discharged suffers more than twice the damage of the same battery that is only discharged to half its capacity. As a result, batteries should be cycled to an optimum average DOD, which varies according to battery chemistry and architecture.

AVAILABLE STORAGE CAPACITY

The available storage capacity is the total amount of energy that a battery can deliver on a single charge. Capacity is one of the most important specifications when selecting a battery. Higher-capacity systems allow for longer periods of backup power.

Capacity is normally expressed in ampere-hours (Ah), which is related to the number of electrons stored within the battery. It is determined by drawing a fixed amperage from a battery until the battery voltage drops below a minimum voltage. The Ah is the product of the constant amperage and the number of hours the battery lasted.

Charge and discharge rates are often given by a C-rate. The C-rate specifies the rate, or amperage, at which a battery is charged or discharged. For example, a 1C charge or discharge rate means that the battery will either be fully charged or discharged after 1 hour. A 0.2C charge or discharge rate means that the battery will either be fully charged or discharged after 5 hours. It is common for battery manufacturers to specify multiple battery capacities at different C-rates for the same battery. This is because the battery experiences higher losses at higher current draws.

Specification sheets often list battery capacity for 100-hour (0.01C), 20-hour (0.05C), 10-hour (0.1C), 5-hour (0.2C), and 1-hour (1C) discharge currents. The energy system design must use the battery capacity that matches the average C-rate that the system will push into or pull out of the battery bank.

Watt-hours (Wh) are an alternative capacity unit frequently used by the telecommunications industry. Available storage capacity, in Wh, is calculated by drawing a fixed power from a battery until the battery voltage drops below a minimum voltage. The Wh is the product of the constant power discharge and the number of hours the battery lasted.

COST OF USE

While the exact lifespan of a battery is unknown, the number of cycles it will last can be estimated from the manufacturer's specifications. The total amount of energy that will be stored and provided to loads over the entirety of the battery's life can be calculated from the battery's estimated lifespan and capacity. The cost of using the battery is then the price of the battery divided by the total amount of energy, or kilowatt-hours (KWh), the battery provides to loads over its lifespan. Lithium-ion batteries, with their longer lifespans, tend to have lower cost of use than lead-acid batteries, even though they are more expensive.

PURCHASE PRICE

Technical papers and reports frequently divide the purchase cost of the battery by its capacity so that the price of batteries with different capacities can be easily compared. However, these normalized battery purchase prices still vary based on differences in battery chemistry, lifespan, performance, and local taxes. System designers and health-care facility managers must balance the need for low purchase prices with low cost of use since cheap batteries tend to have high cost of use.

TEMPERATURE RANGE

Batteries are commonly designed for, and tested at, a specific temperature (usually 25°C). Ambient temperatures above 25°C reduce battery life. Some battery chemistries, such as sealed lead-acid, are more strongly affected by deviations from 25°C than others, such as lithium-ion. As a result, it is common for designers using lead-acid batteries to install climate control equipment into battery rooms to maximize battery lifespan. However, climate control increases system complexity and load; many rural, off-grid health clinics omit climate control and let batteries sit in ambient temperatures. It is important for system designers to compare the cost of the reduced battery lifespan compared to the cost of running the climate control equipment over the life of the battery bank.

MEDIUM IMPORTANCE CONSIDERATIONS

CHARGE/DISCHARGE EFFICIENCY

When creating energy systems for health-care facilities, system designers need to incorporate the battery charge and discharge efficiency into engineering calculations. In many of the facilities where backup battery banks are deployed, electrical energy is at a premium. No matter what power source is charging the batteries, efficient use of that energy is important to the economic and technical performance of the system. High-efficiency batteries equate to smaller solar arrays, lower fuel consumption at a generator, or lower utility bills. Charge and discharge efficiency is closely tied to battery chemistry and construction. Chemistries such as flooded lead-acid batteries that require frequent maintenance charges dissipate large quantities of energy through gassing of the electrolyte and thus are frequently less efficient than lithium-ion chemistries.

MAINTENANCE/DURABILITY

All backup battery systems require some regular preventative maintenance. Some battery technologies and designs, such as sealed lead-acid and lithium-ion batteries, are specifically intended for little-to-no maintenance, while others, such as flooded lead-acid batteries, require regular maintenance charges and careful testing. While it is important to keep maintenance needs low, flooded lead-acid batteries tend to have lower cost of use than sealed lead-acid batteries. To determine if a flooded lead-acid battery is a cheaper storage solution than sealed lead-acid or lithium-ion, facility managers should include the cost of labor, tools, and supplies associated with battery maintenance along with the battery's cost of use.

SELF-DISCHARGE RATE

All batteries naturally lose charge over time. The reasons for this vary depending on the type of battery but often include unwanted chemical reactions or impurities in the battery's materials. The self-discharge rate is the percentage of the battery's capacity that is dissipated over a period of time (e.g., percent/day, percent/month). Because backup power batteries will be constantly connected to chargers, low self-discharge is not critical. It should be noted, however, that higher self-discharge rates ultimately lead to higher overall consumption because more energy must be added to keep the batteries at full charge.

LOW IMPORTANCE CONSIDERATIONS

SIZE/WEIGHT

The size and weight of different battery technologies can be compared in several ways: specific energy (Wh/kilogram (kg)), energy density (Wh/liter), specific power (Watts (W)/kg) or power density (W/liter). While these metrics are very important for applications such as handheld electronics and electric vehicles, they are less relevant when considering a stationary application like backup power. The size and weight of the backup power batteries do not affect their performance, but they will affect the cost of transportation and ease of installation.

BATTERY CHEMISTRIES

LEAD-ACID BATTERY CHEMISTRIES

Invented in 1859, lead-acid batteries are the oldest commercially available battery chemistry and are deployed all over the world in a variety of applications, including automobiles, marine vehicles, and backup power systems. They are also commonly found in off-grid solar and wind installations. Aside from their ability to meet a wide range of technical demands, lead-acid batteries have many advantages over other battery technologies:

- Familiar technology
- Worldwide distribution
- Diverse design options
- Competitive market
- Large knowledge base in backup power applications

Lead-acid batteries are a solid choice for any backup power system, but facility managers must be careful to select the right type of lead-acid battery. Because the lead-acid battery has been in production for so long and is used for many purposes, an array of designs is available. The different design types are most easily defined by their intended application, construction, and materials.

LEAD-ACID BATTERY APPLICATIONS

ENGINE-STARTING

These batteries are found in nearly every production automobile. Designed for engine ignition, they are able to discharge a very high current over a very short period. While these perform well for their intended use, they will do a very poor job under applications demanding high capacity and deep discharge.

DEEP-CYCLE

This design is intended for deep discharge over long periods. Backup power systems and renewable energy storage are where these batteries shine. While they are also able to provide short bursts of high current, they are built to provide a long, sustained, constant current.

MARINE

Boats and other marine vehicles often require both engine-starting and sustained power for onboard electronics. Marine batteries are a hybrid of engine-starting and deep-cycle designs.

LEAD-ACID BATTERY CONSTRUCTION

FLOODED (OR VENTED)

This is the most common and least expensive type of lead-acid battery. Often referred to as ‘wet-cells,’ ‘flooded cells,’ or ‘vented cells,’ these batteries consist of lead plates submerged in a liquid electrolyte solution of sulfuric acid and water. They require regular maintenance as the water concentration declines due to the off-gassing of hydrogen and oxygen.

GEL

These batteries are sealed, valve-regulated lead-acid (VRLA) batteries, meaning they cannot be (and do not need to be) opened for maintenance. Chemically, these are the same as flooded lead-acid batteries except that the sulfuric acid solution is held in a silica gel, rather than in the liquid form. This reduces maintenance requirements and allows the batteries to be mounted in any orientation. For a given capacity and lifespan, gel lead-acid batteries are more expensive than flooded cell batteries.

ABSORBED GLASS MAT (AGM)

AGM is another type of VRLA battery. Like gel lead-acid batteries, the sulfuric solution is not in liquid form but rather is absorbed into fiberglass mats. These batteries have the same low maintenance requirements and flexible mounting orientation as gel batteries. They are less susceptible to damage arising from overcharging than gel VRLAs but more susceptible than flooded batteries.

LEAD-ACID BATTERY MATERIALS

CALCIUM

Most VRLA batteries and engine-starting batteries have calcium added to the lead electrodes. The addition of calcium makes them more resistant to corrosion and overcharging, which leads to lower self-discharge, less maintenance, longer life, and higher max current output.

ANTIMONY

Many industrial and deep-cycle batteries have antimony added to the lead electrodes. Antimony makes these batteries mechanically stronger, allowing for deeper discharges and greater durability. This strength results in a longer service life than calcium batteries. Self-discharge, however, is greatly increased.

LITHIUM-ION BATTERY CHEMISTRIES

Pioneering work on the lithium battery began in 1912 under G. N. Lewis, but commercial development of the lithium-ion battery is rooted in the oil crisis of the late 1970s with independent contributions from Stanley Whittingham, John B. Goodenough, and Akira Yoshino. By the 1990s, lithium-ion batteries had been adopted by portable consumer electronics such as cellular phones. Early use of lithium metal within the battery revealed safety concerns, and so current lithium-ion batteries contain complicated, but safer, lithium alloys to one battery terminal and porous carbon to the other. As a result, battery performance characteristics and cost are heavily dependent on the type of lithium alloy employed within the lithium-ion battery.

Although they are a newer technology and are more costly than lead-acid batteries, lithium-ion batteries can be a more economic storage solution when conditions are right. Lithium-ion batteries are lighter and more compact than lead-acid batteries, allowing battery banks to fit into smaller places, and are cheaper to transport. They have fewer maintenance requirements than a flooded lead-acid battery, reducing battery-related operation costs. Lithium-ion batteries also generally have longer lifespans than lead-acid batteries, reducing battery replacement costs, particularly if batteries are charged and discharged more frequently than once per day. Lithium-ion batteries can also effectively operate within a larger temperature window than lead-acid batteries, reducing or eliminating battery room climate control costs. Lithium-ion batteries are also better able to absorb and supply high currents, making them the preferred storage option when batteries need to supply fewer than 8 hours of load backup.

In addition to higher cost, there are several other disadvantages to using lithium-ion batteries to power health clinics. Lithium-ion batteries can enter an unstable operation regime that results in dangerous battery fires, so larger lithium-ion battery packs usually include a battery monitoring system (BMS) to ensure safe operation. A second disadvantage of lithium-ion batteries is that typically they are not compatible with equipment designed to run off lead-acid batteries. Finally, the lithium-ion battery industry is still developing ways to effectively recycle batteries, while lead-acid battery recycling is well established in many countries.

Lithium-ion batteries have become increasingly more common in health clinics as off-the-shelf solar home system manufacturers have replaced sealed lead-acid batteries with lithium-ion batteries. However, these systems are typically designed to provide lighting only through a few low-power lights. As lithium-ion batteries become increasingly mass produced and manufacturing costs drop, they are increasingly attractive for use in powering health-care facilities. This is largely because they are low maintenance, usually have significantly longer life than lead-acid batteries, and generally do not need to be stored in air conditioning.

PERFORMANCE

LEAD-ACID BATTERY PERFORMANCE

The many designs and applications for lead-acid batteries inevitably lead to a wide range of performance characteristics. As seen in the performance table, lead-acid batteries vary substantially in their technical capabilities.

The performance table highlights the need to be exact when specifying the type and performance of lead-acid batteries for backup power systems. Fortunately, the types of lead-acid batteries suitable for backup power can be narrowed down to those designed for deep-cycle applications. Within this broad category, two main types, in terms of construction and materials, are identified as having the optimal characteristics for this application: flooded antimony lead-acid and VRLA absorbed glass mat.

The comparison table offers a qualitative comparison of the major battery types available for deep-cycle applications. Between flooded lead-acid batteries, lead-antimony stands out as having better deep-cycle performance than lead-calcium, which is a critical characteristic for backup power batteries.

LEAD-ACID BATTERY PERFORMANCE

METRIC	RATING
Nominal Voltage	2.0 V
Cell Capacity	35–5,000 Ah @ 20 hours
Charge/Discharge Rate	0.05C–0.33C
Specific Energy	33–42 Wh/kg
Charge/Discharge Efficiency	60–80%
Self-discharge Rate	1–40% per month
Cycle Life	500–4,200 cycles @50% DOD
Calendar Life	4–25 years
Cost	$100–250 per kWh
Temperature Range	10–35°C

LEAD-ACID BATTERY PERFORMANCE COMPARISON

TYPE	MATERIAL / CONSTRUCTION	COST	DEEP CYCLE PERFORMANCE	MAINTENANCE
Flooded Lead-Acid	Lead-Antimony	Low	Good	High
	Lead-Calcium	Low	Poor	Medium
Valve Regulated Lead-Acid (VRLA)	Gel	Medium	Medium	Fair
	AGM	Medium	Medium	Low

When distinguishing between AGM or gel VRLA batteries, it is important to note that AGMs are generally more robust in design and are less susceptible to damage during charging. Gel VRLAs can become damaged if charged improperly due to the formation of permanent bubbles from gassing. Generally, AGM is preferred over gel VRLAs.

The pros and cons of both flooded antimony lead-acid and AGM VRLA are outlined in the table above. In most cases, the deciding factor when choosing between the two are cost constraints vs maintenance needs.

FLOODED ANTIMONY LEAD-ACID

Pros: These batteries are robust and inexpensive, and they provide excellent deep discharge capabilities, allowing for consistent 80 percent depth of discharge. Because these batteries can deliver the highest capacity and are among the least expensive, they are perhaps the most cost-effective choice.

Cons: Antimony batteries do require high maintenance since much water is lost from gassing, which also requires they be placed in a well-ventilated area. They also have the highest self-discharge rate of any lead-acid battery with rates of 2–10 percent/week.

VRLA ABSORBED GLASS MAT

Pros: AGM batteries are durable and essentially maintenance free. They have better charging capabilities than gel VRLAs. AGMs are also easier to transport and dispose of as there is no risk of leaking acid.

Cons: Recommended depth of discharge is usually around 50 percent but not as good as flooded lead-acid. They are also about 2–3 times more expensive than flooded cell designs.

These battery types will meet the demands of backup power systems. When choosing the specific manufacturer and model, other considerations include the thickness of the lead electrode plates and the manufacturing methods and material quality. The thickness of the plates affects the life of the battery, while manufacturing methods and material quality play a significant role in performance. The quality of a lead-acid battery can be difficult to assess, but generally a high-quality battery can be characterized by higher cost, greater weight, and the length of the manufacturers' warranties.

LITHIUM-ION BATTERY PERFORMANCE


DENNIS SCHROEDER / NREL

Lithium-ion batteries are the primary battery technology used in the electric vehicle industry. Growth within the electric vehicle industry will further reduce lithium-ion production costs, facilitating lithium-ion battery penetration into other markets such as off-grid renewable energy systems. Lithium-ion batteries are already being adopted by manufacturers of pico-solar and solar home system products and are worth considering when designing stand-alone renewable energy systems for off-grid health facilities.

In order to improve safety and performance of lithium-ion batteries, lithium is alloyed with other metals to form the battery cathode. These alloys will produce batteries with different specific energy, power, lifespan, thermal stability (*i.e.*, battery safety), and charging and discharging current handling capabilities (*i.e.*, battery performance). There are six common lithium alloys within commercial markets. They are listed below.

LITHIUM-ION BATTERY PERFORMANCE

ALLOY NAME CHEMICAL COMPOSITION	NOMINAL VOLTAGE	CHARGE/DISCHARGE RATES	CYCLE LIFE	SPECIFIC ENERGY	COST (PER kWh)
Lithium Cobalt Oxide (LCO) $LiCoO_2$	3.60 V	Charging: 0.7C–1C Discharging: 1C	500–1000	150-200 Wh/kg	N.A.
Lithium Manganese Oxide (LMO) $LiMn_2O_4$	3.70 V	Charging: 0.7C–3C Discharge: 1C	300–700	100-150 Wh/kg	N.A.
Lithium Nickel Manganese Cobalt Oxide (NMC) $LiNiMnCoO_2$	3.60–3.70 V	Charging: 0.7C–1C Discharging: 1C	1000–2000	150-220 Wh/kg	$420
Lithium Iron Phosphate (LFP) $LiFePO_4$	3.20–3.30 V	Charging: 1C Discharging: 1C	>2000	90-120 Wh/kg	$580
Lithium Nickel Cobalt Aluminum Oxide (NCA) $LiNiCoAlO_2$	3.60 V	Charging: 0.7C Discharging: 1C	500	200-260 Wh/kg	$350
Lithium Titanate (LTO) Li_2TiO_3	2.40 V	Charging: 1C–5C Discharge: <10C	3000–7000	50-80 Wh/kg	$1,005

LITHIUM COBALT OXIDE

Uses: An obsolete chemistry that was primarily used for phones, tablets, laptops, and cameras.

Pros: High specific energy.

Cons: Short lifespan, low thermal stability (safety), low specific power, high cost of cobalt.

LITHIUM MANGANESE OXIDE

Uses: An improvement on Lithium Cobalt Oxide cells. Commonly used for power tools and medical devices.

Pros: High thermal stability (safety), enhanced safety.

Cons: Short lifespan, average specific energy, low current handling.

LITHIUM NICKEL MANGANESE COBALT OXIDE

Uses: One of the most successful chemistries. Can be tailored to provide improved specific energy or specific power. Preferred lithium-ion chemistry for electric vehicles.

Pros: Low cost of nickel, excellent specific energy, good current handling.

Cons: None.

LITHIUM IRON PHOSPHATE

Uses: Replacement for12-volt automotive battery, energy storage for off-grid renewable energy systems.

Pros: Excellent safety, long lifespan, excellent specific power.

Cons: Low specific energy, elevated self-discharge.

LITHIUM NICKEL COBALT ALUMINUM OXIDE

Uses: Used by Tesla in electric vehicle powertrain applications.

Pros: High specific energy, low cost.

Cons: Low safety

LITHIUM TITANATE

Uses: Electric vehicle powertrains, uninterruptible power supplies, and solar-powered street lighting.

Pros: Very long lifespan, very high safety, high current handling capabilities (performance).

Cons: Very high cost, low specific energy.

CARE AND USE

Lead-acid and lithium-ion batteries have fundamental differences in their placement, charging, and maintenance requirements. At the heart of these differences is a phenomenon that occurs in all lead-acid batteries, known as gassing.

The electrolyte in a lead-acid battery is a solution of sulfuric acid and water. When a battery is being charged, most of the energy being added is used to drive the chemical reactions taking place at the battery's electrodes, thereby restoring the energy that left the battery during discharge. However, excess energy splits water molecules within the electrolyte solution into hydrogen and oxygen gas in a process called electrolysis. In flooded batteries, the hydrogen and oxygen gas produced during normal battery operation are simply released into the surrounding atmosphere. This has two major consequences: (1) a possibly explosive mixture of hydrogen and oxygen has been released, and (2) hydrogen and oxygen (in the form of distilled water) must now be replenished within the cell. Ventilation and maintenance are critical to maintaining the life expectancy of flooded lead-acid batteries. VRLA batteries are not charged to voltages that create the same quantity of the hydrogen and oxygen byproducts, and the little amount that is created is recombined within the battery. Therefore, VRLA batteries do not have the ventilation or maintenance requirements of a flooded lead-acid battery.

In contrast, lithium-ion batteries can only dissipate excess energy to the environment through heat transfer, and if they are overcharged there can be safety concerns. One of the biggest concerns with lithium-ion batteries is that some components within the battery are flammable (like the electrolyte), and if the battery becomes hot enough to enter thermal runaway, the battery can easily ignite. Thermal runaway is a phenomenon when a charging or discharging battery generates more internal heat than it can dissipate, making battery resistance increase which, in turn, generates additional internal heat. The battery's internal temperature exponentially increases to a point where it catches fire. To prevent lithium-ion batteries from reaching thermal runaway, operators should be aware of the safety measures that battery manufacturer's and energy storage system designers put into place to protect the batteries.

LOCATION

When designing and locating a battery bank, the most important considerations are ventilation, mounting, and temperature. While temperature effects are a crucial factor in the performance of any battery, the ventilation and mounting requirements are quite different for flooded lead-acid and VRLA or lithium-ion batteries.

When siting a bank of flooded lead-acid batteries, a well-ventilated area must be chosen. Allowing hydrogen gas to accumulate in an enclosed space heightens the risk of an explosion. Also, easy access to the battery terminals and cell caps is essential for the necessary routine maintenance. Any battery rack or battery box designed for use with wet-cell batteries must accommodate these two constraints.

JERRY BIANCHI / NREL

VRLA and lithium-ion batteries do not vent gas; therefore, ventilation and easy maintenance access are not of great concern. This allows for VRLA and lithium-ion batteries to be housed much closer together. Aside from less stringent ventilation and maintenance requirements, VRLA and lithium-ion batteries also have an advantage in that they contain no liquid. This allows for the batteries to be placed on their side as well as on their bottom. Flexibility in battery orientation is helpful not only when storing the batteries but also during transportation.

Regardless of the type of battery in use, temperature will affect performance. Ideally, batteries should be kept at a temperature of 25°C. Higher temperatures will result in an increase in capacity (Ah) and a decrease in life (cycles). Lower temperatures have an opposite effect, leading to decreased capacity and longer life. Inevitably, battery temperature will deviate from the ideal, due not only to ambient conditions but also to heat generated within the battery itself during charging and discharging.
When siting a battery bank, facility managers should take a couple of simple precautions to minimize temperature fluctuations experienced by the battery. First, a battery bank should be kept out of direct sunlight and away from any other source of heat (e.g., generator exhaust). Second, batteries should not be stored directly on the ground as this will lower their temperature. Keeping the battery bank shielded from heat and insulated from cold will help to ensure top performance.

CHARGING

Charging is a central part of any backup power system. The manner in which a battery is charged plays a significant role in its performance and life. Proper charging will ensure that a battery realizes its full potential in terms of number of cycles and total lifetime output. Different types of batteries require different charging methods in order to maximize efficiency and minimize damage. There are four different modes of charging, each characterized by three interrelated parameters: voltage, amperage, and time. These are:

1. Bulk charging
2. Absorption charging
3. Float charging
4. Equalization charging

Each of these modes plays a different role in the charge cycle.


ANDREW HUDGINS / NREL

Typically, lead-acid batteries regularly undergo the first three charging regimens listed above.
First, the bulk charge applies a constant current to the battery, which gradually increases the battery voltage. This stage normally accounts for 75–80 percent of the total recharge of an empty battery.
The second charging stage is absorption, which is characterized by a constant charging voltage that provides decreasing amperage into the battery as the battery increases its state of charge. This stage safely charges the battery to full charge, which is said to occur when the current drops to a rate of 0.02C. Maintaining the correct constant voltage throughout the absorption stage is important to battery life and performance and will vary depending on the type of battery (e.g., AGM deep cycle, flooded lead-antimony). The final charge in the three-stage charging process is the float charge, which is designed to counteract the battery's natural self-discharge and keep the battery at full capacity.

While these three charge modes are generally applicable to any lead-acid battery, each type of lead-acid battery and even different manufacturers will have specific voltage and amperage requirements for each mode. In order to ensure optimum battery performance and life, all batteries should be charged in accordance with manufacturer specifications. Since these charging parameters are a function of battery design and construction, they will vary depending on a number of factors; it is, however, possible to make some overarching observations. For example, the absorption charge is commonly performed at a higher voltage for flooded lead-acid batteries than for VRLA (gel and AGM) lead-acid batteries. This is because the gassing that occurs in all lead-acid batteries occurs primarily during absorption charging. In a flooded lead-acid battery, this process is necessary and helps to keep the electrolyte solution well mixed. Any hydrogen lost from the cell will be replaced in the form of distilled water during maintenance. In sealed VRLA batteries, however, water cannot be replaced, so any venting of gasses will affect battery life. Gel VRLAs are especially sensitive to gassing as small bubbles will form in the silica gel, resulting in permanent damage.

A fourth mode of battery charging is the equalization charge. Equalization charging is not a part of the typical charging cycle and is typically only performed periodically on flood lead-acid batteries on an as-needed basis. As batteries are regularly charged and discharged, the chemical composition of each cell can become disturbed. Electrolyte stratification, the concentration of acid at the bottom of the cell, and sulfation, the buildup of sulfate crystals on the surface of the lead electrodes, are two problems that naturally occur in lead-acid batteries. An equalization charge helps to reverse these problems and keep the battery operating at optimum performance.

Lithium-ion batteries can be charged in a similar staged manner as lead-acid batteries; however, lithium-ion batteries are charged at different voltages and do not have a mechanism to dissipate extra energy once battery cells are full. Thus, the charging regime for a lithium-ion battery has different voltage set points to transition from bulk charge to absorption charge and lacks the float and equalization charge. Continuing to charge a lithium-ion battery beyond its maximum voltage will shorten its lifespan and could push it into thermal runaway.

In order to achieve the correct charging sequences, carried out at the correct voltages and charge rates, a charge controller is necessary. Many different types of chargers exist, from manually controlled constant voltage chargers to sophisticated microprocessor-controlled chargers. In the case of an inverter/battery backup system, the inverter (the piece of equipment responsible for converting between AC and DC current) also acts as the battery charger. Such inverter/charger systems are capable of properly recharging, float charging, and discharging a battery bank based on battery specifications and connected loads. While inverter/chargers are preprogrammed to perform the complete charging regimen, it is important that the voltage and amperage set points be programmed based on battery manufacturer specifications.

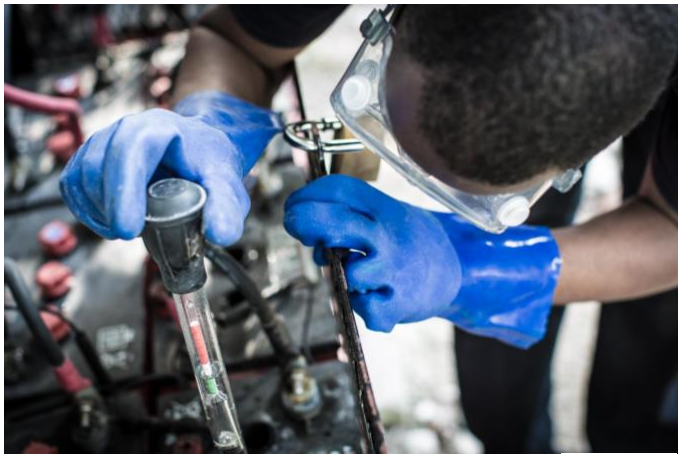
Temperature will affect optimal charging parameters, and some manufacturers will provide temperature-corrected voltage specifications. In fact, many advanced charge controllers, such as inverter/chargers, will allow for the use of a temperature sensor and will automatically apply a temperature-corrected voltage.

PROTECTION CIRCUITS AND BATTERY MANAGEMENT SYSTEMS

All lithium batteries have some form of protection to prevent ignition of the lithium battery. In basic lithium-ion cells, these protection measures can include a fuse and a pressure vent. However, for larger batteries, lithium-ion battery pack manufacturers add external circuitry that measure voltages, currents, and temperatures throughout the battery to detect potential abuse. If the circuitry detects a potential problem, it can take action to prevent thermal runaway. A protection circuit is an off-the-shelf chip found on smaller lithium-ion batteries that detects individual cell voltages within a battery and disconnects the cells when voltages are too high or too low. Battery management systems (BMS) are more complicated computer-controlled systems for larger battery banks that can measure voltage, current, and temperature over tens or hundreds of cells. BMS are frequently enabled with communication ports to allow inverters to receive charging/discharging voltage set points or error messages from the BMS.

MAINTENANCE

As previously discussed, flooded lead-acid batteries need regular maintenance and monitoring, while sealed VRLA and lithium-ion batteries are far less maintenance intensive. In either case, there are some simple maintenance activities that should be periodically undertaken.



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Battery systems should be kept clean. Dirt and even acid will inevitably accumulate on lead-acid batteries, inverters, and cables that are the part of an energy system; these should all be cleaned as needed. With flooded lead-acid batteries especially, acid will mist out of the vented caps and settle on the battery casings. A basic solution (*i.e.*, baking soda and water) can be used to neutralize the acid. A clean battery will ensure that there is no parasitic electrical current running between the battery terminals, increasing the self-discharge rate. The frequency of such maintenance will depend on where the batteries are located; housing them away from dirt and activity will help to minimize the need for cleaning.

Safety precautions are necessary when properly maintaining a flooded lead-acid battery. Because this maintenance entails the handling of acid, eye protection (and preferably a full face shield) and thick rubber gloves must be worn. If battery acid gets on clothing, it will disintegrate the fibers, so old or protective clothing should be worn.

Testing the specific gravity of flooded lead-acid battery cells is the only way to be sure that the batteries are chemically sound. The specific gravity of a solution is the ratio of the solution's density over pure water. With the battery's cell caps open, a specific gravity electrolyte tester is used to draw the electrolyte solution out of the battery cell, at which point a reading can be taken. At 25°C and 100 percent charge, a battery should have a specific gravity of 1.260. Each cell should be checked to ensure that the specific gravity is equal among all cells. While the battery is open, it is also important to check the fluid levels within each cell. There should be no exposed metal surfaces. If a cell requires a recharge of water, it must be distilled water. The cell should be filled to the level dictated by the manufacturer.

VRLA and lithium-ion batteries do not need to be checked for specific gravity or fluid levels within the cell, just periodic cleaning. For any battery, the best recommendation is to follow all of the manufacturer's maintenance and charging specifications.

RECYCLING

Lead-acid batteries enjoy a very high rate of recycling. This is due primarily to the high value of lead, much of which is used in the production of new lead-acid batteries. In fact, 97 percent of all battery lead is recycled, and new batteries contain 60–80 percent recycled lead and plastic. Used lead-acid batteries are collected and then processed in a recycling facility. The batteries are first smashed to pieces and then put into a separating vat, where the lead, plastic, and electrolyte solution are separated into different recycling streams for processing. Recycled lead and plastic from batteries is often used in the production of new batteries. The electrolyte solution can be used in the production of glass, textiles, and ceramics or neutralized and treated as waste water.

Lead-acid battery recycling is one of the most successful examples of a closed-loop recycling process. In order for that process to succeed, however, regulations must be in place and strictly enforced. For many countries in the developing world, this is not the case. Since lead is still highly valuable around the world, lead-acid battery recyclers are prevalent. In many cases, those recyclers are not equipped, trained, or motivated to properly process batteries. Improper processing and handling of those batteries has a negative effect on human and environmental health. Any project employing lead-acid batteries, especially in an effort to increase human and environmental health, should ensure that proper facilities and oversight are available for the recycling process.

While more than 99 percent of lead-acid batteries are recycled, only about 5 percent of lithium-ion batteries are recycled in the United States and Europe. The number of lithium-ion batteries recycled in developing countries is going to be even lower because lithium-ion batteries are relatively difficult to recycle. This difficulty stems from the non-standardized form factors, difficulty of disassembling a battery, wide variety of chemical compositions, and low concentrations of individual metals within the lithium-ion battery that prevent automation and easy quantification of the economic return of recycling lithium-ion batteries. For example, the average lead-acid batteries are approximately 65 percent lead, while the average lithium-ion batteries contain 2.2 percent lithium, 2.8 percent cobalt, 8.5 percent aluminum, 15 percent nickel, and 17 percent copper.

The environmental and social impact of manufacturing new lithium-ion batteries and disposing of used ones is great, but the industry struggles to recycle a significant number of used lithium-ion batteries. It takes 250 tons of mineral ore or 750 tons of lithium-rich brine to make one ton of lithium. The extraction of lithium ore and brine significantly impacts the surrounding environment and population. Lithium-ion manufacturing's use of cobalt is also of concern. The largest reserves of cobalt are found within the Democratic Republic of Congo, where small-scale mining raises significant environmental and ethical concerns (including child labor). At the same time, the chemicals used within lithium-ion batteries—cobalt, nickel, manganese, and lithium fluoride salts—are toxic to the environment and human beings and easily leach out of batteries thrown into landfills.