Battery Chemistry Comparison: Lead Acid, Li-ion, LiFePO4

The purpose of this paper is to demystify the relationship between various battery chemistries typically used in BESS and UL compliance. Li-ion, LiFePO4, and Lead Acid battery chemistries will be used for comparison. Regarding testing, UL 9540A (which tests thermal runaway) will be our prime example. It is important to note that while Li-ion technically refers to all batteries that use lithium chemistry, common parlance typically refers to LiFePO4 as a unique term. 'Li-ion,' therefore often refers to specific lithium chemistries that include cathode materials such as nickel, cobalt, and manganese. 'LiFePO4' describes lithium batteries which specifically and exclusively use phosphate as the cathode material in the chemical process. In this paper, 'Li-ion,' will cover a range of lithium chemistries that exclude LiFePO4 to draw clear distinctions.

Let us first agree on the spirit of things. That is–safety. Whether it be a manufacturer, regulator, or end user, we all need safety. So with that said, code compliance is more than just a list of rules; it's about ensuring that our technologies and practices meet the highest performance and reliability standards. Not only that, but by embracing and even exceeding these standards we can cultivate creativity in a way that ultimately benefits everyone. This leads us to the evolution of battery chemistry as it stands today.

Broadly speaking, battery chemistry has evolved directly from lead-acid technology to lithium-ion over time (which is where we are today). But, is one battery chemistry preferable over another? Specifically, is there a safer and more reliable chemistry, or, are they all very similar? Let's take a look at what sets each apart, specifically regarding the advantages and disadvantages.

We've broken this down into four main points:

1: Battery Chemistry:

- **Chemistry(Lead-Acid):** Uses lead dioxide and lead in a chemical process. During discharge, the chemical reactions convert lead and lead dioxide into lead sulfate. Charging reverses this process.

- **Chemistry(Li-ion):** Encompasses a variety of lithium-based chemistries, including but not limited to Lithium Cobalt Oxide ($LiCoO_2$), or Lithium Nickel Manganese Cobalt Oxide (NMC). They are typically very energy-dense.

- **Chemistry(LiFePO4):** Specifically uses phosphate as the cathode material. These types of batteries benefit from a high current rating and long life cycle as well as excellent thermal stability and enhanced safety tolerance. This is because it is more tolerant to full-charge conditions than other Li-ion systems.

2. Energy Density:

- **Energy Density(Lead-Acid):** Relatively low energy density, resulting in heavier and bulkier batteries.

- **Energy Density(Li-ion):** Lithium-cobalt chemistries provide the highest energy density, allowing for the lightest weight and most compact design among chemistry variants.

- **Energy Density(LiFePO4):** Moderate energy density, balancing energy storage and weight.

3. Expected Lifespan:

- **Lifespan(Lead-Acid):** Short life cycle, around 300-500 cycles on average. Should not be discharged below 50% regularly to avoid significant capacity loss. Frequent routine maintenance is required.

- **Lifespan(Li-ion):** Medium life cycle, around 500-1000 cycles on average. Can be discharged to 60% or more without significant capacity loss. Some routine maintenance is required.

- **Lifespan(LiFePO4):** Longest life cycle, around 2000 - 7000 cycles, or more on average. Can be discharged to 80% without significant capacity loss. Some routine maintenance is required.

4: Safety, of course:

- **Safety(Lead-Acid):** While generally safe, these batteries risk thermal runaway and can even become explosive. This is largely due to the hydrogen gas released during charging and can be exacerbated by high temperature, high float voltage, and pressure.

    - **Thermal Runaway Risk:** While lead-acid batteries can experience thermal runaway (a self-reinforcing overheating process), it is less common and less severe than in lithium-ion batteries.
    - **Hydrogen Gas:** The primary safety concern with lead-acid batteries is the production of hydrogen gas during charging. This gas is flammable and explosive if allowed to accumulate in an enclosed space. Proper ventilation and maintenance are crucial to mitigate this risk.
    - **Other Factors:** High temperatures, overcharging, and physical damage can also increase the risk of lead-acid battery failure or accidents.

- **Safety(Li-ion):** Prone to thermal runaway, leading to fire and/or explosions. Damage or improper handling can exacerbate the potential for failure/hazard. One example of this might be an internal short.

    - **Thermal Runaway:** Li-ion batteries are more prone to thermal runaway than lead-acid batteries, especially in specific chemistries like Lithium-Cobalt Oxide (LCO). This can lead to fire or explosion.
    - **Internal Shorts:** Internal shorts caused by manufacturing defects or damage can trigger thermal runaway.
    - **Mitigating Risks:** Li-ion batteries often have built-in safety features like vents, thermal fuses, and battery management systems (BMS) to mitigate risks. Proper handling and charging are also essential.

- **Safety(LiFePO4):** Extremely safe, as it is the most stable of all current battery chemistries and presents a very low risk of overheating or catching fire. Preferable when safety is critical.
    - **Extremely Safe:** LiFePO4 batteries are considered the safest among common lithium-ion chemistries. They have a very low risk of thermal runaway and are more tolerant of overcharging and high temperatures.
    - **Chemical Stability:** The inherent chemical stability of LiFePO4 contributes to its safety.
    - **Safety-Critical Applications:** LiFePO4 is often the preferred choice for applications where safety is paramount, such as energy storage systems and electric vehicles.

At EG4, we manufacture LiFePO4 batteries specifically. We chose this chemistry because its stability, cost-effectiveness, and efficiency allow us to deliver a product that readily passes UL 9540A. Each of our batteries has undergone testing and passed this trial at the unit level. This means they have been tested and evaluated regarding fire safety hazards associated with thermal runaway and have been found safe. In addition, the National Fire Protection Association (NFPA) code 855 sets the standard for installing Stationary Energy Storage Systems (SESS). NFPA 855 specifically looks at whether or not a particular system or part of a system passes UL 9540A testing. Users of EG4 batteries can count on these systems to provide the power they need without the headache, hassle, and hazard of risking a fire. Not only that, at EG4 we've built-in dual fire arrestors to our batteries, just in case.

We also designed the world's first "Total E-Stop" for BESS systems. Essentially, this tiny red button allows you to shut down your entire system (batteries, PV, inverters) with one single push. This is helpful not only for homeowners but also for first responders. Firefighters must shut down power to a home when attempting to make a breach, and the Total E-stop makes their job quick and easy.

In summary, UL 9540A plays a crucial role in ensuring the safety of energy storage systems across various battery chemistries, with LiFePO4 being a standout among them for its unique stability. By adhering to this test method, manufacturers can demonstrate compliance with fire safety standards and provide safer technologies for homes, businesses, and beyond!

(See table below for quick comparisons.)

Feature	Li-ion Batteries	LiFePO4 Batteries	Lead-Acid Batteries
Chemistry	Various chemistries like LiCoO2, NMC, etc.	Lithium Iron Phosphate (LiFePO4)	Lead dioxide (PbO2) and sponge lead (Pb)
Energy Density	150-250 Wh/kg	90-120 Wh/kg	30-50 Wh/kg
Safety	Moderate to high risk of thermal runaway	Very safe, high thermal stability	Safe but can release hydrogen gas
Cycle Life	300-1000 cycles	2000-7000+ cycles	300-500 cycles
Discharge Rate	Varies, generally high	High	Moderate
Temperature Performance	Degrades at extreme temperatures, especially heat	Good high-temperature performance	Poor performance at low temperatures
Cost	High	Moderate	Low
Maintenance	Low	Low	High (regular maintenance needed)
Weight	Light	Light	Heavy
Charge Time	1-3 hours	1-3 hours	6-12 hours
Environmental Impact	Less toxic, recycling is complex	Less toxic, easier to recycle	Highly toxic, easier to recycle
Applications	Consumer electronics, electric vehicles, renewable energy storage	Electric vehicles, solar energy storage, power tools	Automobiles, backup power, industrial equipment