



(RESEARCH ARTICLE)



Batteries as an integral part of Microgrids: Can LiFePO₄ batteries be an efficient solution in the future?

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Abstract

The integration of batteries as a pivotal component of microgrids represents a transformative shift in energy management and distribution. Batteries, serving as critical energy storage systems, enhance the resilience, reliability, and sustainability of microgrids by enabling efficient energy storage and distribution. This paper explores the multifaceted role of batteries within microgrids, emphasizing their ability to store excess renewable energy, manage peak demand, and provide backup power during grid outages. Through a comprehensive analysis of current technologies, economic viability, and environmental impact, this study highlights the benefits and challenges associated with the deployment of battery systems in microgrids. Furthermore, it examines case studies from diverse geographic regions to illustrate the practical applications and advantages of battery-integrated microgrids in promoting energy independence and sustainability.

Keywords: Microgrid Energy Storage(MES); Battery Energy Storage System(BESS); Renewable Energy Integration(REI); Solid State Batteries(SSB); Smart Grid Technologies(SGT); Lithium-Ion Batteries(Li-ion); Constant Current(CC); Constant Voltage(CV)

1. Introduction

In the evolving landscape of energy systems, microgrids have emerged as a cornerstone of decentralized power generation and distribution, offering enhanced control and flexibility over energy resources. At the heart of these microgrids, batteries play an indispensable role by providing the necessary infrastructure for efficient energy storage and management. As global energy demands rise and the shift towards renewable energy accelerates, the capacity of batteries to store and redistribute energy becomes increasingly vital.

Microgrids, typically comprising localized networks of distributed energy resources (DERs), rely on batteries to balance supply and demand, mitigate fluctuations in energy production from renewable sources, and ensure continuous power supply during disruptions. Batteries within microgrids serve multiple functions: they store surplus energy generated from renewables, facilitate load leveling to reduce peak demand, and provide essential backup power, thereby enhancing the overall reliability and resilience of the energy system.

This paper aims to delve into the integral role of batteries within microgrids, exploring their technological advancements, economic implications, and environmental benefits. We will analyze various battery technologies, including lithium-ion, flow batteries, and emerging solid-state batteries, assessing their suitability for microgrid applications based on factors such as energy density, efficiency, lifespan, and cost.

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2. Materials and Methods

2.1. What are microgrids?

A microgrid is a small-scale, localized power network that integrates multiple distributed energy resources (DERs) such as renewable energy generators, conventional energy sources, and energy storage systems. It is designed to supply electricity to a specific geographic area, which can range from a single building to a community or a campus. Microgrids can operate in two modes:

- Grid-Connected Mode: Where they are connected to the main utility grid.
- Island Mode: Where they function independently from the main grid, typically during power outages or disturbances.
- Key Features:
 - Local Energy Generation: Microgrids use local energy resources, including renewable sources (solar, wind, biomass) and sometimes conventional sources (natural gas, diesel generators).
 - Energy Storage: They incorporate energy storage systems, such as batteries, to store excess energy generated and provide backup power during demand peaks or grid outages.
 - Control Systems: Microgrids are equipped with sophisticated control systems to manage the balance between supply and demand, ensure stability, and optimize energy use.
 - Flexibility and Reliability: They offer high reliability and flexibility by providing a resilient energy supply that can quickly respond to changing conditions, such as outages or fluctuations in energy demand.
 - Sustainability: Microgrids support sustainable energy practices by integrating renewable energy sources, thus reducing greenhouse gas emissions and reliance on fossil fuels.
 - Economic Benefits: They can reduce energy costs by optimizing the use of locally generated energy and decreasing dependence on the central grid.
 - Energy Independence: Microgrids enhance energy security and independence, making them particularly beneficial for remote or isolated areas where grid connection is unreliable or unavailable.
 - Scalability: They are scalable and can be designed to meet the energy needs of small communities or large industrial complexes.

Applications

- Remote Areas: Providing energy in regions where grid connection is impractical or too costly.
- Critical Infrastructure: Ensuring continuous power for hospitals, data centers, military bases, and other critical facilities.
- Urban Areas: Enhancing energy resilience and supporting the integration of renewable energy in cities and towns.
- Industrial Complexes: Offering reliable and cost-effective energy solutions for industrial operations and manufacturing facilities.

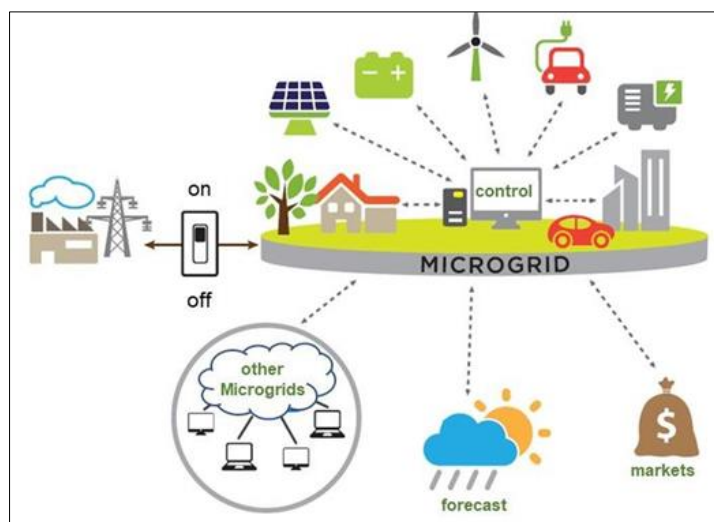


Figure 1 Microgrid

2.2. Main reason for using microgrids

The main reason behind the concept of a microgrid is Energy storage. Energy storage is a flexible, versatile, and distributed energy resource that can significantly benefit a microgrid. Besides encouraging more renewable electricity generation, improved storage technologies have a lot of other benefits.

Storing energy in the microgrids is an essential part as per the future aspect of a microgrid. Microgrids consume a massive amount of power and energy to distribute electricity and various other resources. So, in order to put our focus more towards it, we should look at storing the energy for longevity and which can be used in emergency cases as well.

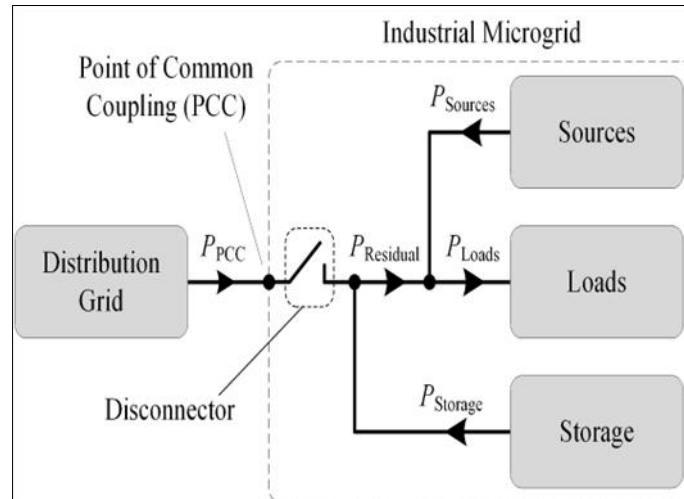


Figure 2 Layout of an Industrial Microgrid

2.3. Best source of storing energy:

2.3.1. Battery Energy Storage System(BESS)

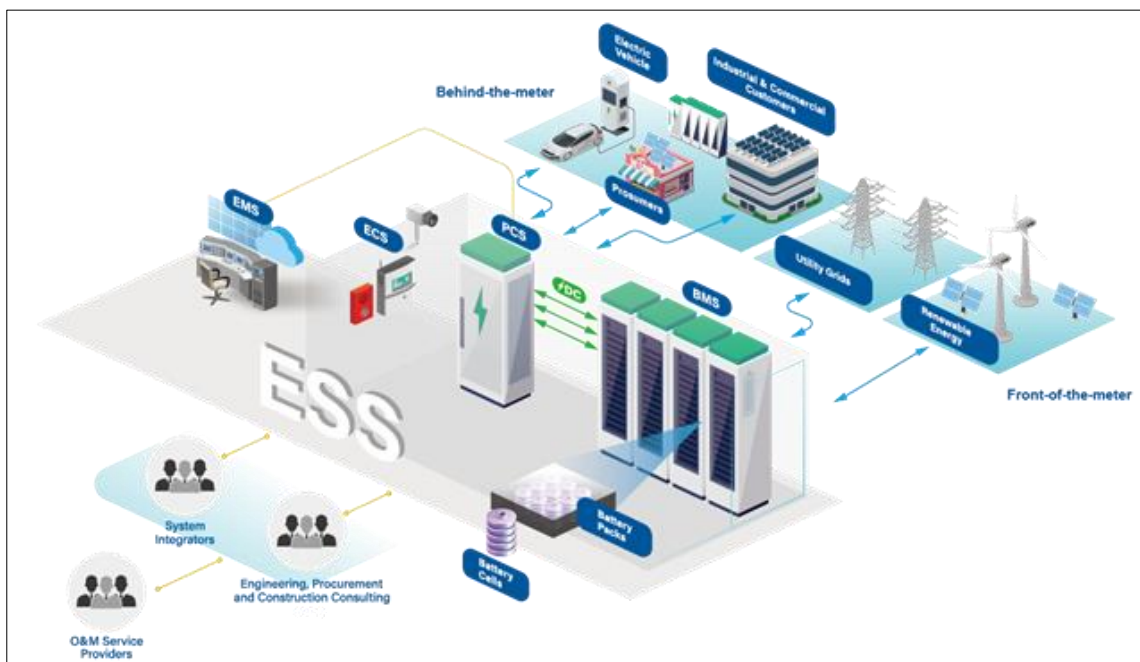


Figure 3 Battery Energy Storage System(BESS)

They use lithium-ion, magnesium-ion, or another of a variety of options to store generated energy. Residential energy storage in backup power applications usually supports the energy needs in case the grid suffers a failure. Should there be a grid disruption, energy can be pulled from the batteries as far as the allowable discharge depth has been met.

Batteries also come with different capacities. The microgrid owner should determine the amount of energy produced by the system before purchasing the storage batteries. Once the maximum output has been determined, batteries with the matching capacity can be purchased and integrated into the system. Should the microgrid go down, solar and wind provide a battery charging source, expanding the backup power accessibility from a specific period of hours per day. Batteries usually store energy during the peak production hours when the output is in oversupply. This bridges the gap when energy production during the night for solar panels or when the wind is not blowing. Batteries will also regulate peak consumption when the AC grid has been stressed to the breaking point.

2.3.2. Types of Batteries used for storing energy

Table 1 Li-Ion Battery v/s Lead Acid Battery

Lithium - Ion Battery	Lead Acid Battery
Lowest Total Lifetime cost	Medium upfront cost
Useable SoC 10-90%	Usable Capacity 50%
Ultrafast Charging Profile	Slow Charging Profile
95% Average Lifetime Round Trip efficiency	<65% Average Lifetime Round Trip Efficiency
Less Charging Time	Excess Charging Time
Closed Loop Integration with inverter/charger	No Smart Integration with Charger
Maintenance Free	High Maintenance

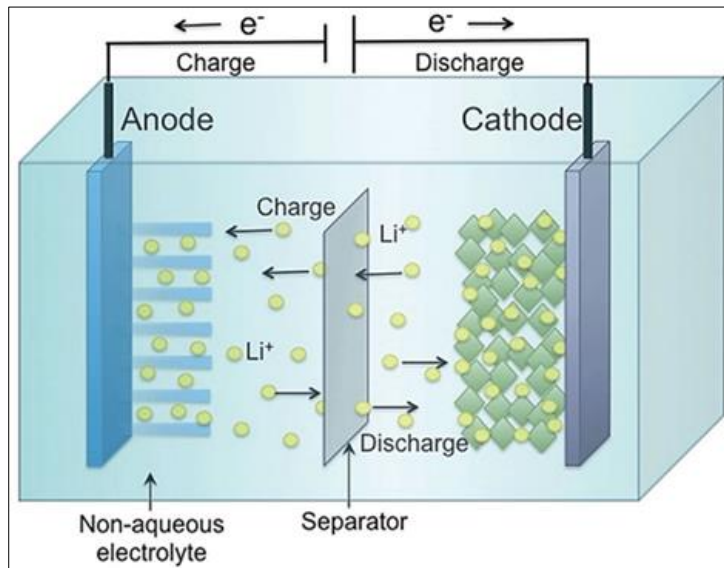


Figure 4 Lithium Ion Battery

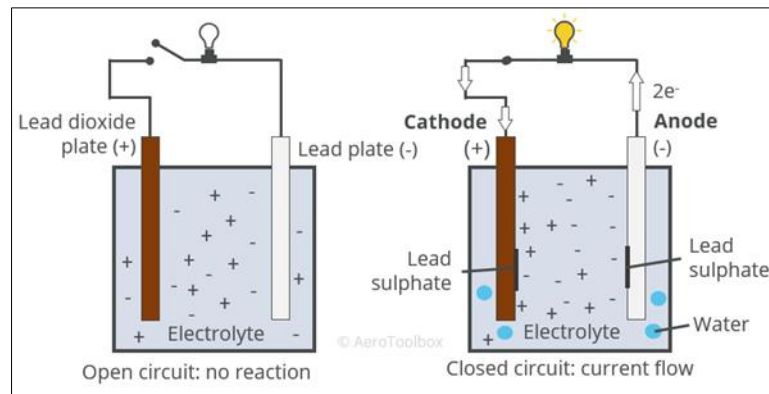


Figure 5 Lead Acid Battery

2.4. Graphical Representation of various aspects with respect to Li-Ion and Lead Acid Batteries

2.4.1. Charging Aspect

Lithium-Ion

Lithium-ion (Li-ion) batteries are renowned for their efficient and fast-charging capabilities, making them a preferred choice for many modern applications, including electric vehicles (EVs) and portable electronics. Li-ion batteries typically feature a high energy density and low self-discharge rates, allowing for longer periods between charges. The charging process for Li-ion batteries is generally divided into two stages: constant current (CC) and constant voltage (CV). During the CC phase, the battery is charged at a constant current until it reaches a specific voltage threshold. Then, it enters the CV phase, where the voltage is held steady while the current gradually decreases until the battery is fully charged. This method helps in achieving a quicker recharge while minimizing the risk of overcharging, which can lead to safety issues or reduce battery life. The absence of memory effect in Li-ion batteries allows for flexible charging cycles without significant degradation in capacity. However, it is crucial to monitor temperature during charging, as excessive heat can lead to safety concerns, including the potential for thermal runaway.

Lead-Acid Batteries

Lead-acid batteries, one of the oldest rechargeable battery technologies, are widely used in automotive applications, backup power systems, and uninterruptible power supplies (UPS). The charging process for lead-acid batteries is relatively slower compared to Li-ion batteries and typically involves three main stages: bulk charge, absorption charge, and float charge. In the bulk charge phase, the battery receives a large current to quickly bring the voltage up to about 80-90% of its capacity. The absorption stage then reduces the current while maintaining a constant voltage to charge the remaining 10-20%, ensuring the battery reaches full capacity without overcharging. Finally, the float charge maintains the battery at a reduced voltage to compensate for self-discharge and ensure the battery remains fully charged. This method is effective in maintaining the longevity of the battery, though lead-acid batteries are prone to sulfation if left in a discharged state for too long, which can reduce capacity and lifespan. Additionally, lead-acid batteries are sensitive to charging temperatures, as both high and low temperatures can negatively affect charging efficiency and overall battery health.

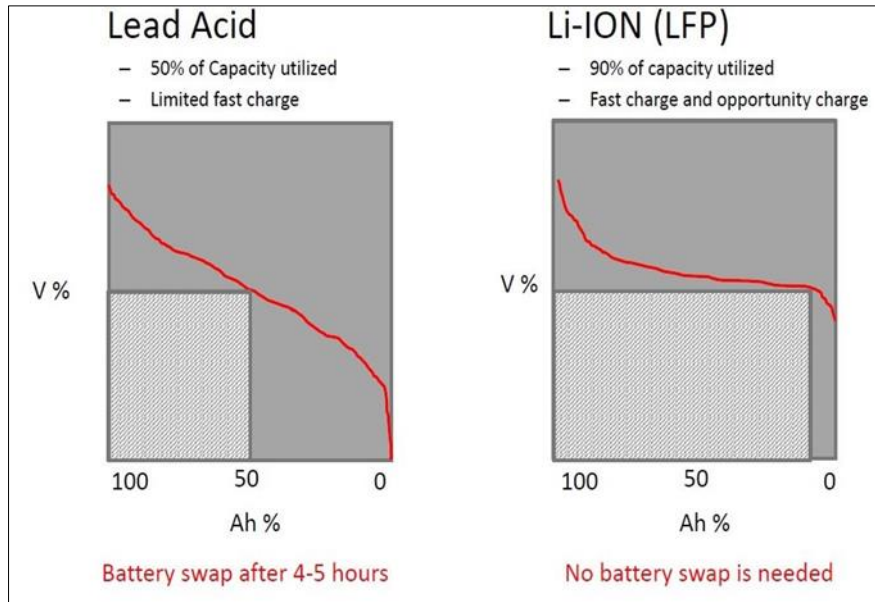


Figure 6 Charging Aspect Ft. Lead Acid v/s Li-Ion Battery

2.4.2. Depth of Discharge (DoD) Curve

Lithium-Ion Batteries

The depth of discharge (DoD) curve for lithium-ion (Li-ion) batteries is typically characterized by a relatively flat and consistent voltage drop throughout the discharge cycle, making them highly efficient for various applications. Li-ion batteries can sustain deeper discharge levels (up to 80-90% DoD) without significantly affecting their cycle life, which refers to the number of charge-discharge cycles a battery can endure before its capacity significantly degrades. This characteristic makes Li-ion batteries ideal for applications requiring frequent and deep discharges, such as electric vehicles and portable electronics. The voltage of a Li-ion battery remains relatively stable until it reaches a low state of charge (SoC), after which the voltage drops sharply. This flat voltage profile helps in delivering consistent performance over a wide range of discharge levels, and the battery's advanced internal management systems can accurately monitor and manage DoD to prevent over-discharge, which can damage the battery and reduce its lifespan.

Lead-Acid Batteries

The depth of discharge (DoD) curve for lead-acid batteries shows a more pronounced voltage drop as the battery is discharged, with a significant reduction in voltage as the DoD approaches higher levels. Lead-acid batteries are generally more sensitive to deep discharges compared to Li-ion batteries and typically have an optimal DoD of around 50%. Discharging a lead-acid battery beyond this level can drastically reduce its cycle life and lead to sulfation, where lead sulfate crystals form on the battery plates, impairing its ability to hold charge. As a result, lead-acid batteries are often used in applications where they can be maintained at a partial state of charge (SOC) and where deep discharges are infrequent, such as in automotive starter batteries or stationary backup power systems. The steep decline in voltage at higher DoD levels also necessitates careful monitoring to avoid excessive discharge, which can lead to permanent damage and reduced overall battery efficiency.

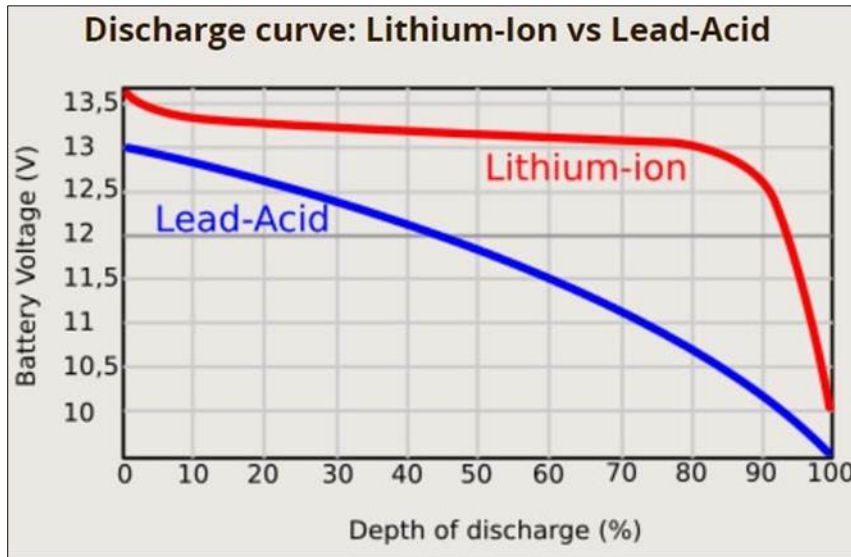


Figure 7 Depth of Discharge Curve Ft. Lead Acid v/s Li-Ion Battery

2.5. Lithium Iron Phosphate (LiFePO₄) – Can it be a probable solution in the future??

Lithium iron phosphate (LiFePO₄) batteries are a specific type of lithium-ion battery with distinct characteristics and advantages, particularly in applications requiring safety, long life, and stability. Below is a discussion on the depth of discharge (DoD) curve and other features of LiFePO₄ batteries in the context of their application in lithium advanced energy storage (AES) systems.

2.5.1. Depth of Discharge(DoD) Curve

Lithium iron phosphate (LiFePO₄) batteries exhibit a unique depth of discharge (DoD) curve compared to other lithium-ion chemistries. The DoD curve of LiFePO₄ batteries is characterized by a stable and flat voltage profile throughout most of the discharge cycle. This flat voltage characteristic ensures that the battery provides a consistent voltage output, which is crucial for applications requiring a steady power supply. Even when discharged to higher levels, typically up to 80-90% DoD, LiFePO₄ batteries maintain a relatively consistent voltage until they approach a low state of charge (SOC), at which point the voltage drops more rapidly.

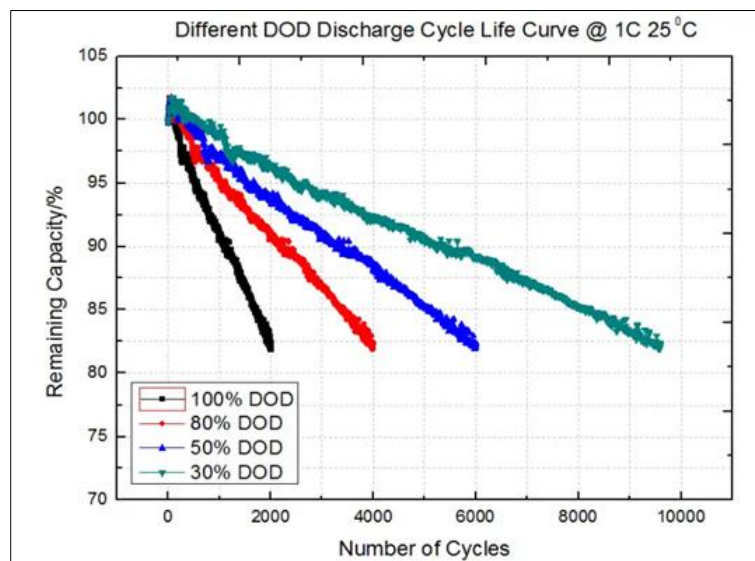


Figure 8 DoD Curve – LiFePO₄

This stable voltage profile makes LiFePO_4 batteries highly reliable and predictable in terms of performance. Furthermore, LiFePO_4 chemistry supports a large number of charge-discharge cycles, often exceeding 2000 cycles even with deep discharges, which contributes to a longer battery lifespan. The ability to withstand deep discharges without significant degradation makes LiFePO_4 batteries an excellent choice for energy storage systems where frequent cycling and high reliability are required, such as in renewable energy storage or backup power systems.

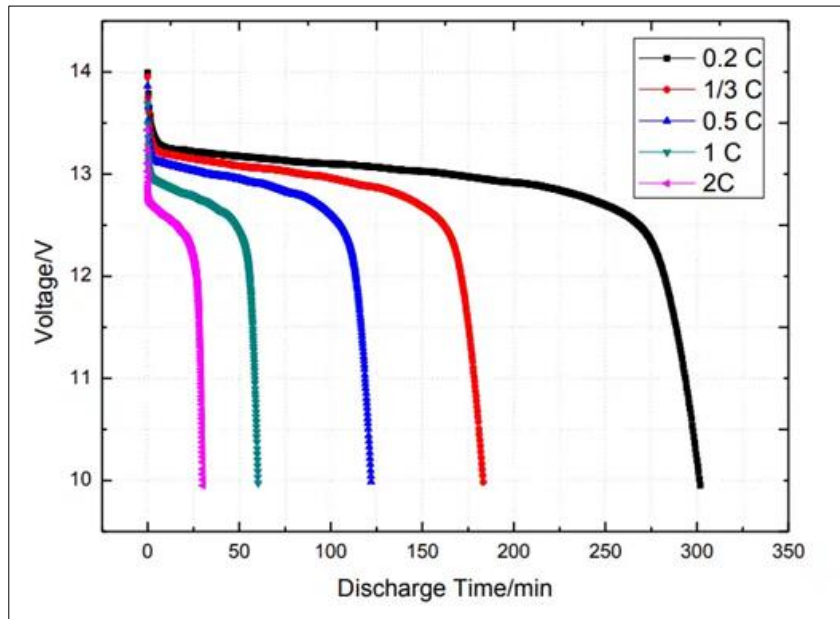


Figure 9 LiFePO_4 Discharge and Charge Curve

The above graph shows “Graphical Analysis of Capacity Retention as a Function of Discharge Current for LiFePO_4 and Lead-Acid Batteries”. This comparative analysis highlights the performance differences between the two battery technologies under different load conditions.

LiFePO_4 Batteries

The graph indicates that LiFePO_4 batteries exhibit a stable capacity retention across a wide range of discharge currents. As the discharge current increases, the capacity of LiFePO_4 batteries remains relatively constant, showcasing a gradual and slight decline. This stability is primarily due to the inherent properties of LiFePO_4 chemistry, which includes low internal resistance and high thermal stability. These characteristics enable the batteries to efficiently manage high discharge rates without significant loss of capacity or performance. The minimal decrease in capacity at higher currents makes LiFePO_4 batteries ideal for applications requiring consistent energy output over varying conditions, such as in electric vehicles, power tools, and renewable energy storage systems.

Lead-Acid Batteries

In contrast, the capacity retention of lead-acid batteries demonstrates a more pronounced decline as discharge current increases. The graph shows a steep drop in capacity with higher discharge rates, indicating that lead-acid batteries struggle to maintain their efficiency under high current loads. This rapid decrease in capacity can be attributed to the higher internal resistance and lower chemical stability of lead-acid batteries. These factors cause increased energy losses and heat generation, leading to reduced performance and quicker depletion of available energy. Consequently, lead-acid batteries are better suited for applications with lower discharge currents where the demand for rapid energy release is minimal, such as in stationary energy storage, backup power systems, and certain automotive applications.

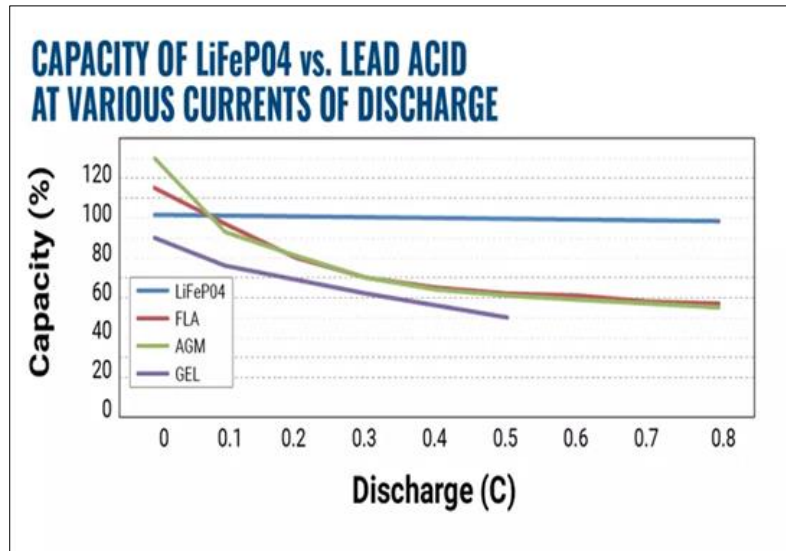


Figure 10 Capacity Retention Ft. LiFePO₄ v/s Lead Acid Battery

2.5.2. Key Features of Lithium Iron Phosphate (LiFePO₄) Batteries in AES

- **Safety and Stability:** LiFePO₄ batteries are known for their thermal and chemical stability, reducing the risk of thermal runaway and making them safer than other lithium-ion chemistries. This makes them suitable for applications where safety is paramount, such as in electric vehicles and residential energy storage.
- **Longevity:** LiFePO₄ batteries have a long cycle life due to their ability to handle deep discharges without significant loss of capacity. This longevity is a critical factor for applications where the battery is expected to last for many years.
- **High Current Capability:** These batteries can deliver high currents, making them suitable for applications requiring high power output, such as grid storage and electric propulsion systems.
- **Environmental Friendliness:** LiFePO₄ batteries do not contain cobalt, which is a toxic and expensive material found in other lithium-ion batteries. This makes them more environmentally friendly and cost-effective in the long term.
- **Temperature Tolerance:** They have a wide operating temperature range, which makes them suitable for use in various environmental conditions, including extreme temperatures.
- **Lower Energy Density:** One of the trade-offs is that LiFePO₄ batteries have a lower energy density compared to other lithium-ion chemistries, such as lithium cobalt oxide (LiCoO₂). This means they store less energy per unit weight or volume, which can be a limitation in applications where space or weight is a critical factor.

Table 2 Why LiFePO₄ is better?

LiFePO ₄ Characteristics:
Manufactured with the highest-grade cells and a proprietary high peak surge and transient BMS.
Maintenance Free
100% Depth of Discharge
Upto 98% Round Trip Efficiency
Unlimited Cycle 10 Year Energy Throughput Warranty

2.6. Comparative Analysis b/w LiFePO₄ v/s Lead Acid v/s Lithium Ion Battery

Table 3 LiFePO₄ v/s Lead Acid v/s Lithium Ion Battery

Characteristics	LiFePO ₄	Lead Acid	Li-Ion
Energy Density	Moderate (90-160 Wh/kg)	Low (30-50 Wh/kg)	High (150-260 Wh/kg)
Cycle Life	High (2000-5000 cycles)	Low (200-500 cycles)	Moderate (500-1500 cycles)
Charge/Discharge Efficiency	High (>90%)	Moderate (70-80%)	High (90%)
Capacity Retention	Stable across a range of currents	Significant drop at high currents	Moderate, can drop at high currents
Discharge Rate	High	Low	High
Charging Speed	Fast (1-2 Hours)	Slow (8-10 Hours)	Fast (1-4 Hours)
Safety	Very safe, thermally stable	Moderate, risk of leaks and explosions	Moderate, risk of overheating and fire
Environmental Impact	Low Toxicity, environmental friendly	High Toxicity, hazardous material	Low to moderate, depending on type
Cost	Moderate to High	Low	High
Weight	Light	Heavy	Light
Maintenance	Low	High, regular maintenance required	Low
Temperature Tolerance	Wide Range (-20°C to 60°C)	Narrow Range (-10°C to 45°C)	Moderate Range (0°C to 45°C)
Self Discharge Rate	Low (2-3% per month)	High (5-20% per month)	Moderate (5-10% per month)
Recyclability	High	High, but complex due to lead	Moderate to High

3. Conclusion

In comparing LiFePO₄, lead-acid, and lithium-ion batteries, LiFePO₄ stands out for its long cycle life, safety, and stable capacity retention across various discharge currents, making it ideal for electric vehicles and renewable energy storage. Lithium-ion batteries excel with high energy density and fast charging, suitable for consumer electronics and electric vehicles, albeit with safety considerations due to overheating risks. Lead-acid batteries, though cost-effective and reliable for backup power and stationary applications, lag in energy density, cycle life, and efficiency, requiring more maintenance and posing significant environmental concerns due to toxic lead content. Overall, LiFePO₄ and lithium-ion offer superior performance and longevity, though at a higher initial cost compared to lead-acid batteries.

On the other hand, Microgrids is a very interesting concept which is already in use. What I feel is that while we focus on the energy storage problem, where we can use these microgrids in a very effective way in our future. We can use microgrids on a much larger scale than it can be anticipated. We can supply power and energy if when there is no source. The stored energy in the batteries will be enough to supply the resources to wherever required. Microgrids will be a very effective tool in supplying the power, energy and resources in our future. If and when we solve the energy storage issue, we would be able to store large quantity of resources and energy and use it efficiently.

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