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COMPARATIVE ANALYSIS OF ELECTRIC VEHICLE BATTERY TECHNOLOGIES: PERFORMANCE, SAFETY, AND SUSTAINABILITY

Alimnazarov Adkham
Tashkent State Technical University Master's student
alimnazarovadham0@gmail.com
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Abstract. Electric vehicles (EVs) depend on rechargeable batteries to provide driving range, power, and reliable operation. Battery chemistry affects vehicle mass, charging time, cost, safety, and environmental impact. This article reviews the main battery technologies used in electric vehicles: lead–acid, nickel–metal hydride (NiMH), lithium iron phosphate (LFP), nickel manganese cobalt oxide (NMC), nickel cobalt aluminum oxide (NCA), lithium titanate (LTO), sodium-ion, and solid-state batteries. A comparative literature-review approach is used to assess energy density, durability, thermal behavior, charging performance, and application suitability. Lithium-ion batteries remain the leading technology for modern electric vehicles. LFP batteries offer favorable thermal stability and durability, while NMC and NCA batteries generally provide higher energy density. Sodium-ion batteries may become useful in cost-sensitive applications, while solid-state batteries require further development. Battery selection should consider vehicle requirements, climate, safety, lifecycle cost, and recycling.

Keywords: electric vehicles, battery technology, lithium-ion batteries, LFP, NMC, energy density, battery safety, thermal management, sustainability.

1. INTRODUCTION. Electric vehicles are an important part of the transition toward more energy-efficient transportation. Unlike conventional vehicles, battery electric vehicles store electrical energy in rechargeable batteries and use electric motors for propulsion. They can reduce local exhaust emissions and improve drivetrain efficiency, although their overall environmental impact also depends on electricity generation and battery production.

The traction battery is a major vehicle component because it influences driving range, acceleration, charging time, mass, and operating cost. A suitable battery must store sufficient energy, deliver power reliably, charge within an acceptable time, and operate safely over a wide range of temperatures. These requirements involve trade-offs: high-energy batteries can reduce mass for a given range, while other chemistries may provide lower cost, better thermal stability, or longer cycle life.

Lead–acid batteries are still used in auxiliary electrical systems, and nickel–metal hydride batteries remain established in hybrid vehicles. Lithium-ion batteries dominate modern battery electric vehicles because they combine relatively high energy density, good efficiency, and mature manufacturing. Within this family, LFP, NMC, and NCA differ in cost, energy density, and thermal behavior. Sodium-ion and solid-state batteries are also being developed, but their long-term competitiveness depends on safety, durability, manufacturing scale, and cost.

The objective of this article is to compare the principal battery technologies used in electric vehicles and summarize their technical characteristics, safety considerations, environmental implications, and suitability for different applications.

2. MATERIALS AND METHODS. This study uses a comparative literature-review method. Scientific reviews and technical reports were considered to summarize battery chemistry, specific energy, charging behavior, cycle life, thermal stability, material availability, and

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automotive applications. The technologies were grouped into established automotive batteries, commercial lithium-based batteries, and emerging systems.

The review did not include new laboratory experiments. Therefore, numerical ranges presented below are indicative values reported in technical literature. Actual performance varies with cell design, operating temperature, charge rate, test procedure, and whether the reported value refers to an individual cell or a complete battery pack.

The comparison uses several criteria. Specific energy describes the energy stored per unit mass, while volumetric energy density describes energy stored per unit volume. Cycle life indicates the number of charge–discharge cycles before capacity falls to a defined threshold. Thermal stability, charging capability, material requirements, cost, and recycling potential are also considered. No single criterion is sufficient to determine the best battery for every vehicle.

3.RESULTS AND DISCUSSION. Battery structure and operating principle. A rechargeable battery contains electrochemical cells with a positive electrode, negative electrode, electrolyte, separator, and current collectors. During discharge, chemical reactions produce electrical energy that powers the vehicle. During charging, an external source reverses these reactions. In lithium-ion batteries, lithium ions move between electrodes through the electrolyte, while electrons flow through the external circuit.

Cells are connected in series and parallel to provide the required voltage and capacity. A complete battery pack also includes protective housing, sensors, electrical connections, a battery management system (BMS), and thermal-management equipment. These supporting systems are important because cell performance alone does not determine pack-level reliability.

Table 1. Main battery components and their functions

Component	Function	Importance
Positive and negative electrodes	Store and release ions during electrochemical reactions	Determine capacity, voltage, and aging behavior
Electrolyte and separator	Enable ion movement while preventing direct electrode contact	Support operation and reduce short-circuit risk
Battery management system	Monitors voltage, current, and temperature	Helps protect the battery and balance cells
Thermal-management system	Controls battery temperature	Supports charging, performance, and service life

Established battery technologies. Lead–acid batteries use lead-based electrodes and a sulfuric acid electrolyte. They are relatively inexpensive, can provide high short-duration current, and have established recycling systems. Their main disadvantage is low specific energy, typically about 30–50 Wh/kg. Their high mass makes them unsuitable for most long-range EVs as the main traction battery, so they are mainly used for auxiliary electrical systems.

Nickel–metal hydride (NiMH) batteries use a nickel-based positive electrode and a hydrogen-absorbing alloy negative electrode. They provide reliable power delivery and have been widely used in hybrid vehicles, where batteries frequently accept regenerative-braking energy and provide additional acceleration power. Their specific energy is commonly around 60–120 Wh/kg, lower than that of many modern lithium-ion cells.

Lithium-based batteries. Lithium-ion batteries are the main energy-storage technology in modern battery electric vehicles. Their advantages include relatively high specific energy, good electrical efficiency, and flexible pack design. However, their performance depends on the electrode chemistry.

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LFP batteries use lithium iron phosphate as the positive-electrode material. They offer good thermal stability, long cycle-life potential, and do not require nickel or cobalt in the cathode. They are often suitable for urban vehicles and commercial fleets. Their main limitation is lower energy density than many NMC and NCA cells, and low temperatures can reduce charging capability.

NMC batteries contain nickel, manganese, and cobalt in the positive electrode. Their composition can be adjusted to balance energy density, stability, and durability. They are useful when long driving range and compact battery packaging are priorities. NCA batteries use a nickel-rich cathode containing cobalt and aluminum and can also provide high energy density. Both NMC and NCA systems require suitable thermal control and careful charging management.

LTO batteries use lithium titanate as the negative-electrode material. They can support rapid charging, high power, and frequent cycling, but their energy density is generally lower than that of conventional high-energy lithium-ion cells. They may therefore be useful in specialized fleet applications where charging time and cycle life are more important than minimum battery mass.

Table 2. Indicative comparison of battery technologies

Technology	Typical specific energy (Wh/kg)	Main advantage	Main limitation
Lead–acid	30–50	Low cost; mature recycling	High mass
NiMH	60–120	Reliable hybrid operation	Lower energy density
LFP	Approx. 120–205	Thermal stability and durability	Lower energy density than many nickel-rich cells
NMC	Approx. 150–265	High energy density	Material supply and thermal control
NCA	Product-dependent; high-energy class	High energy per unit mass	Requires careful thermal and electrical control
LTO	Generally lower than high-energy graphite-anode cells	Rapid charging and cycle durability	Lower energy density

Note: These are approximate literature-based ranges, not universal product specifications. Cell and pack values should not be compared directly without checking the measurement basis.

Comparison of LFP and NMC. LFP and NMC are two important choices for electric passenger vehicles. LFP batteries generally provide favorable thermal stability and avoid nickel and cobalt in the cathode. They are often attractive for vehicles with predictable daily routes and regular charging. NMC batteries generally provide higher energy density, allowing more energy to be stored in a given mass or volume, which can benefit long-range vehicles.

The International Energy Agency reported that LFP batteries represented more than 55% of EV batteries deployed globally in 2025. Its analysis also identifies lower energy density but cost advantages for LFP compared with NMC packs [1]. The best choice nevertheless depends on the vehicle's range, battery packaging, climate, charging requirements, and expected service life.

Table 3. Practical comparison of LFP and NMC

Criterion	LFP	NMC
Energy density	Generally lower	Generally higher
Thermal behavior	Favorable stability	Depends on composition and

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		system design
Cathode materials	No nickel or cobalt required	Nickel and cobalt are used
Typical priority	Cost and durability	Range and compact packaging
Key consideration	Cold-weather charging performance	Thermal control and degradation

Emerging technologies. Sodium-ion batteries use sodium ions rather than lithium ions. Sodium is widely available, and some designs may reduce dependence on critical minerals. However, many sodium-ion cells have lower energy density than leading lithium-ion products. Their potential applications include smaller EVs and cost-sensitive transport, provided that commercial performance and manufacturing economics are competitive.

Solid-state batteries use a solid ion-conducting electrolyte instead of a conventional liquid electrolyte. They may enable higher energy density and new electrode designs. However, interface stability, manufacturing complexity, cost, and long-term durability remain important challenges. Their future role will depend on results from large-scale production and real-world testing.

Table 4. Emerging battery technologies

Technology	Potential benefit	Main challenge	Possible application
Sodium-ion	Resource availability and supply diversification	Energy density and cost	Small EVs and selected commercial vehicles
Solid-state	Potential for high energy density	Interfaces and scalable manufacturing	Future high-performance EVs
Recycled materials	Reduced demand for primary resources	Recovery efficiency and material quality	Circular battery supply chains

Battery management, safety, and sustainability. The battery management system monitors cell voltage, current, and temperature, and helps keep operation within permitted limits. It estimates state of charge and battery health, controls charging and discharging, and balances cells. Effective management cannot stop aging completely, but it can reduce avoidable degradation.

Temperature strongly affects battery performance. High temperatures can accelerate aging and increase safety risks, while low temperatures can reduce power and restrict charging. Air cooling is relatively simple, whereas liquid cooling usually provides better heat transfer under demanding conditions. Battery heating may also be required in cold climates.

Battery production has environmental impacts associated with mining, material processing, manufacturing, transportation, and end-of-life management. LFP avoids nickel and cobalt in the cathode, but the overall environmental impact also depends on electricity sources, manufacturing energy, battery lifetime, and recycling. Recycling can recover valuable materials, while batteries that no longer meet vehicle requirements may be reused for stationary storage if their condition and safety are verified.

Economic evaluation should include purchase price, energy consumption, charging expenses, maintenance, degradation, replacement, and end-of-life value. The lowest initial price does not necessarily mean the lowest total cost over the vehicle's service life.

Table 5. Battery operating risks and mitigation

Factor	Possible effect	Mitigation
High temperature	Faster aging	Cooling and temperature monitoring
Cold charging	Reduced charging capability;	Preheating and current limits

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	degradation risk	
Excessive voltage or current	Cell damage and heat generation	BMS protection and controlled charging
Cell imbalance	Reduced usable capacity	Cell balancing
Poor storage conditions	Accelerated calendar aging	Follow manufacturer guidance

CONCLUSION. This review shows that no single battery technology is optimal for every electric vehicle. Lead–acid batteries remain useful for auxiliary systems, while NiMH batteries are established in hybrid vehicles. Lithium-ion batteries dominate modern battery electric vehicles because of their energy density, efficiency, and technological maturity.

LFP batteries offer favorable thermal stability, durability, and reduced dependence on nickel and cobalt. NMC and NCA batteries are useful where higher energy density and longer driving range are priorities. LTO batteries may suit specialized applications requiring rapid charging and frequent cycling. Sodium-ion batteries offer supply-chain opportunities, while solid-state batteries remain under development.

Battery selection should consider driving range, vehicle mass, climate, charging infrastructure, safety, cost, and recycling. Effective battery management and thermal control are essential for reliable operation. Future research should improve battery durability, increase energy density without compromising safety, develop efficient recycling, and validate emerging technologies under realistic conditions.

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