

Driving Electric Mobility: Classification and Application Perspectives of Battery Technologies

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Abstract

The rapid pace of the electric vehicle (EV) adoption has increased the importance of high-performance, safety and cost-effective battery technologies. Even with significant advancements, no single battery chemistry can satisfy the ever-increasing demands for low cost, environmental sustainability, rapid charging, thermal stability, high energy density and extended cycle life. This poses a critical problem to researchers and manufacturers in choosing and optimizing battery systems in various use in EVs. In this paper, a systematic and comparative review of prominent battery technologies utilized in electric vehicles, such as lead-acid, nickel-metal hydride (NiMH), lithium-ion (Li-ion) variants of nickel-manganese-cobalt (NMC) and lithium iron phosphate (LFP) as well as new solid-state and sodium-ion batteries are discussed. The comparative metrics are key evaluation parameters, which include the energy density, power density, cycle life, charging characteristics, safety performance, thermal behaviour, cost factors and material sustainability. A performance-based evaluation system is created to evaluate the trade-offs between the various chemistries and their applicability to various EV types such as hybrid, passenger and commercial vehicles. However, there are still problems with end-of-life management, thermal runaway and reliance on raw materials. Emerging technologies like solid-state and sodium-ion batteries have potential. In order to support the next generation of electric mobility, this work provides a thorough technological foundation for battery selection with an emphasis on material innovation, battery management systems and sustainable lifespan approaches.

Keywords: Electric Vehicles, Lithium-Ion Batteries, Lithium Iron Phosphate (LFP), Solid-state Batteries, Energy Density, Battery Management System

1. Introduction

The growth of electric vehicles (EVs) has quickened the demand of effective and dependable battery technologies. As batteries are the primary source of energy in the EVs, their properties directly influence the driving range, operational safety, speed of charging, cost and the efficiency of the vehicle. So, the selection of an appropriate battery chemistry is a design decision. A battery present in EVs is normally classified as primary and secondary. Primary batteries are not rechargeable and cannot be transported, but secondary batteries can be charged and discharged again and again, and are necessary in electric mobility applications [1]. State of charge (SOC) is also a vital aspect of any EV system since it can be used to estimate the remaining capacity and

make reliable predictions of the range. Safe charging and discharging, performance optimization, and fast-charging strategies are also guaranteed by good battery modelling. Electrochemical models are some of the methods of analysis that are available; they are highly precise because they analyse internal chemical reactions and the microscopic behaviour of battery hence, they are useful in the analysis of advanced battery management systems [2]. EV rechargeable batteries are further classified based on the electrochemical makeup. Lead-acid batteries are still prevalent in the automotive, storage and communications areas due to their cheap cost and technological stability. But there is an increasing concern over handling big volumes of discarded

units. These batteries are filled with lead plates, sulfuric acid and polypropylene casings, which can pollute the environment when they are not properly treated. [3]. The creation of lead-carbon fibre composite (LCF) materials is supposed to improve the service life of the LABs by increasing charging reactions, supporting electrodes, and serving as a capacitor in the high rate of operation. It has been demonstrated that LCF insertion can reduce internal resistance and enhance chargeability in general [4]. Researchers have also infused carbon-based materials in lead-acid systems in order to improve performance. Lead-carbon fibre composites, such as, enhance the acceptance of charge, decrease the internal resistance and increase the operational life. Innovative pulse-based regenerative charging methods have also been provided to alleviate sulfation and increase durability in industrial operations including material-handling vehicles [5]. Nickel-based batteries were invented in order to address some of the limitations of the lead-acid systems. Nickel-cadmium batteries have a better cycle life and high-rate discharge capacity, although the environmental issues surrounding cadmium toxicity and memory effect have restricted its use. NiMH batteries became more acceptable in terms of the environment and became popular in hybrid cars. The current studies in the NiMH technology involve improved anode materials, including perovskite-based compounds, in order to improve discharge capacity and electrochemical kinetics [6]. Moreover, the recycling process is also being considered in a sustainable way to extract useful metals out of old NiMH batteries to serve environmental responsibility and efficiency of the resources [7]. Recent studies are directed towards the improvement of Li-ion and other battery chemistries. Aluminium-modified nickel oxyhydroxide compounds are proven to be superior in energy density and cycling behaviour in aqueous magnesium-ion battery systems with novel cathode materials. Aqueous magnesium-ion batteries (AMIBs) are promising owing to the abundance of magnesium, its safety and high theoretical capacity, despite the low ion diffusion rate and poor stability. On-going research in materials and system design is to provide safer, efficient and sustainable energy storage systems that will be used in electric vehicles

[8]. Lithium-ion (Li-ion) batteries have become most popular among the existing technologies because they offer a high energy density, lightweight and their electrochemical performance is high. Different cathode materials are used in Li-ion cells, such as lithium cobalt oxide (LiCoO_2), lithium manganese oxide (LiMn_2O_4), lithium iron phosphate (LiFePO_4), nickel-manganese-cobalt oxides (LiNiMnCoO_2) and nickel-cobalt-aluminum oxides (LiNiCoAlO_2), each with some pros and cons. These batteries come in cylindrical, prismatic and pouch forms and are common in EVs and hybrid vehicles, aerospace and communication systems [9]. It is also important to dispose and recycle Li-ion batteries in a responsible manner. Different recovery methods are under development such as mechanical separation, pyrometallurgical processing, hydrometallurgical extraction and direct material regeneration to recover useful metals and minimize environmental impact [10]. In all battery chemistries, current studies focus on the enhancement of energy density, cycling stability, rate capability and material sustainability [11]. Besides, second-life applications are also attracting interest as retired EV batteries are used in stationary energy storage system to fully utilize resources and increase their service life [12]. The lithium-based batteries have great performance benefits but there are various challenges that prevent their sustainability at a large scale. The cost of high production, safety risk, environmental issues and effective end-of-life management are still the burning issues. Battery Management Systems (BMS) are necessary to guarantee a stable operation by monitoring the voltage, current and temperature levels and prevent overcharging and deep discharge of cells and thermal stress. State of Charge (SoC) and State of Health (SoH) estimation and cell balancing techniques are performed by advanced BMS algorithms to ensure similar performance of battery packs which enhances the durability and operational safety [13]. In spite of their superiority, lithium-ion batteries have limitations including the scarcity of lithium and safety risks associated with dendrite growth and flammability of liquid electrolytes. The application of the lithium-ion technology in energy storage is used in small residential systems up to large-scale, grid-scale systems. Safe operation is

subject to proper estimation of SoC and operation within the recommended limits especially when many cells are linked in series and parallel. Reliability and safety in big battery packs, uniformity is critical and thermal or electrical imbalance should be avoided [14]. Current studies are aimed at improving battery material and system components. To achieve high capacity and improved stability, advanced electrode materials including silicon or germanium-based anodes, layered compounds, phosphate-based cathodes and nanostructured metal oxides. Solid electrolytes, improved separators and other thermal management schemes with the inclusion of phase change materials and nanofluids are also innovations to control temperature and extend life [15]. Computational methods like Density Functional Theory (DFT) are used to determine the ionic transport and adsorption in new materials, including defect-engineered MXenes, in both lithium-ion and sodium-ion systems [16]. The use of solid-state batteries is a significant development, substituting liquid electrolytes with solid conductors with a significant enhancement in safety, thermal stability and potentially energy density [17]. Meanwhile, sodium-ion batteries are cheaper alternative since sodium is found naturally. Studies in this field focus on new cathode materials, electrolyte, interface and recycling [18]. There are also struggles to improve low-temperature performance and the creation of new carbon and two-dimensional-based electrodes to satisfy future energy storage needs in an environmentally responsible way [19]. This paper gives detailed review on battery types in section II and characteristics of different batteries in section III and finally the application perspectives in section IV.

2. Types of Batteries

2.1. Lead Acid Batteries

One of the oldest battery technologies that are rechargeable is the use of lead-acid batteries which were first used in early electric vehicle prototypes. They are characterized by cheapness, easy production process and reliability. They however have low energy density, heavy, exhibit low cycle life and slow charging properties. These are limited by the fact that they are not applicable to the modern EVs but they are applied to the auxiliary power.

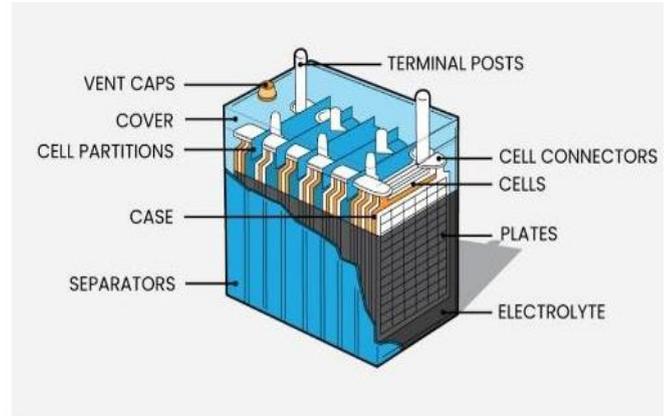


Figure 1 Structure of Lead-Acid Battery

2.2. Nickel-cadmium Battery



Figure 2 Structure of Ni-Cd Battery

Batteries made with nickel and cadmium offer higher energy density and cycle life than lead based batteries. They can work under the conditions of high discharge rates and under severe environmental conditions. Nonetheless, there is an environmental and disposal problem of toxic cadmium. Also, Ni-Cd batteries are affected by memory effect and this is a limitation to effective capacity unless controlled. Nickel-cadmium batteries cannot be used in EVs because of their low energy and considerable memory effect and self-discharge which restrict range and efficiency of driving. Also, the amount of cadmium toxicity is a significant issue that creates serious environmental and regulatory issues which would make it impossible to roll out EV on a large scale. Subsequently, nickel-metal hydride batteries became a superior technology in comparison to Ni-Cd. They have increased energy density, enhanced environmental safety and less memory effect.

2.3. Nickel-cadmium Battery

The NiMH batteries were common in the early hybrid electric vehicles (HEVs) due to their durability and average price. They are however less energy dense and have a higher

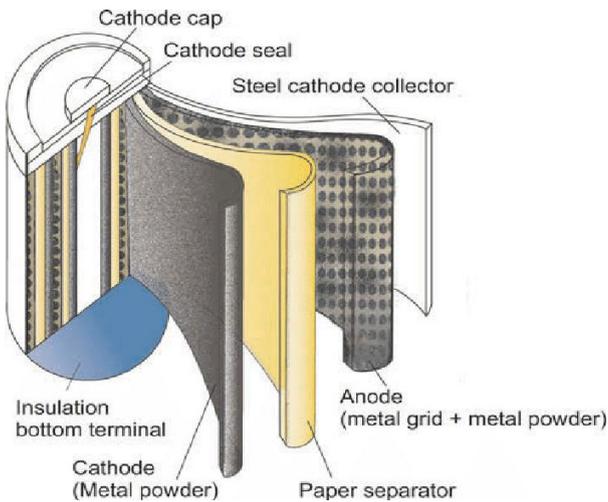


Figure 3 Dissection of Ni-MH Battery

self-discharge rate compared to lithium-ion batteries and this restricts their application in long range fully electric cars.

2.4. Lithium-ion Battery

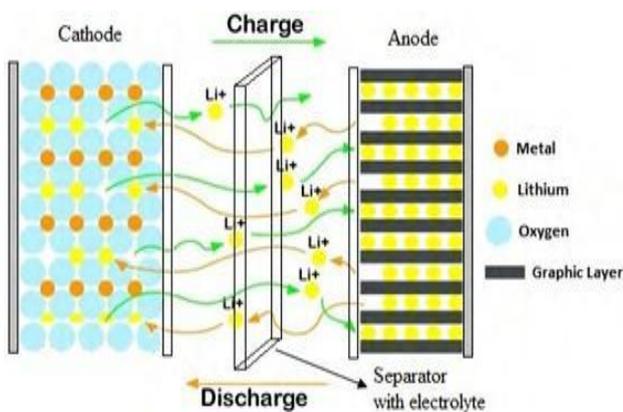


Figure 4 Charging & Discharging of Li-Ion Battery

The most popular technology in electric vehicles is currently Lithium-ion batteries. They have high energy density, high power capability, lightweight structure, long cycle life and high coulombic efficiency. They do not show any major memory effect unlike Ni-Cd batteries. They have a relatively

lower self-discharge rate and their manufacturing costs are on the decline which has increased the rate at which they are commercialized in the EV industry. A variety of lithium-ion chemistries such as lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC) and lithium cobalt oxide (LCO) are designed to meet particular performance goals such as safety, energy density or cost optimization. Li-ion batteries have been the battery of choice because of their high-performance properties in the current electric mobility. Lithium-ion batteries are nearing their theoretically achievable performance limits, so researchers are looking at alternative chemistries, including lithium-sulphur, sodium-sulphur, sodium-metal chloride and metal-air batteries. The goals of these technologies are to attain greater specific energy, reduced material cost and enhanced sustainability. Despite these potentials, many of these systems continue to have technical issues with regard to cycle life, stability, and large-scale commercialization.

2.5. Solid-state Battery

Solid-state batteries are a high-technology energy storage medium that employs solid rather than liquid or gel electrolyte as in the case with traditional lithium-ion batteries. With classic batteries, the movement of lithium ions between the cathode and anode is carried out by a liquid medium. By comparison, solid state batteries allow the passage of ions via a solid medium like a ceramic, sulphide or polymer.

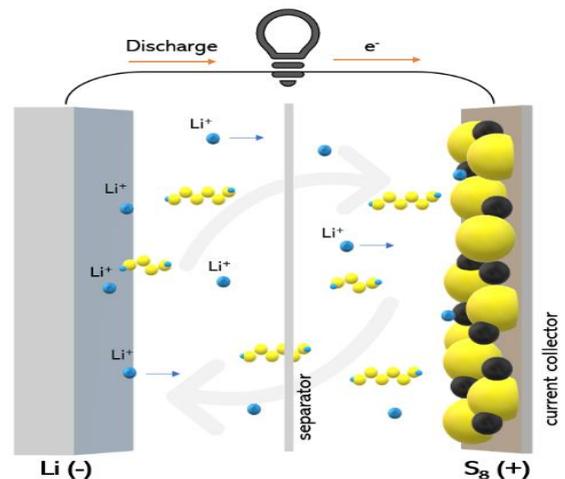


Figure 5 Li-S Battery Working Principle

Solid-state batteries are a high-technology energy storage medium that employs solid rather than liquid or gel electrolyte as in the case with traditional lithium-ion batteries. With classic batteries, the movement of lithium ions between the cathode and anode is carried out by a liquid medium. By comparison, solid state batteries permit flow of ions through a solid substance. This is an important structural change, which enhances safety, energy density and long-term reliability. Solid-state technology is one of the most promising advances toward next-generation electric vehicles, portable electronics and grid storage systems.

2.6. Sodium-ion Battery

Sodium-ion batteries are becoming attractive as a substitute of lithium-ion systems because of the issue of lithium supply and the environmental effect.

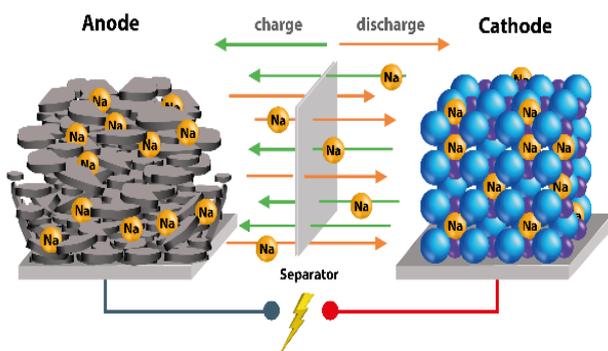


Figure 6 Sodium -Ion Battery Structure

The lithium deposits are geologically clustered and pose supply threats and price volatility. The extraction and processing of the lithium and cobalt lead to environmental decline, excessive energy use and waste products. These drawbacks have promoted the creation of more sustainable and more affordable energy storage technologies. Sodium-ion batteries are also a prospective solution as sodium is universal, cheap and its distribution is uniform throughout the planet. The development of electrode materials, electrolytes and cell format has made SIBs substantially better in the electrochemical performance of these materials which has enhanced their energy density, cycling stability and safety attributes. Continued studies are aimed at maximizing the cathode materials (layered oxides and polyanionic compounds) and hard carbon anodes

to maximize capacity and rate capability. SIBs are under investigation to use in electric vehicles (EVs) and energy storage systems (ESS). Although there has been variability in EV demand because of safety and the shortage of charging infrastructure, the stationary energy storage industry has only grown as a response to the global carbon reduction targets. Despite the fact that lithium-ion batteries remain most popular in the markets of EVs and ESSs, their cost fluctuation and materials limitations encourage the development of sodium-based solutions. On the whole, sodium-ion batteries are an economical and greener alternative with high potential of large-scale energy storage. Further material innovation and optimization of manufacturing should enable them to be even more competitive in the next-generation battery applications.

3. Characteristics of Batteries Used in Electric Vehicles

Battery technology is a critical issue in the performance, safety, cost and sustainability of electric vehicles (EVs). The various battery chemistries have their own benefits and constraints and they can be used in a particular application like hybrid cars, passenger EV or commercial electric buses. Here, the comparison of the key types of batteries utilized in EVs: Lead-Acid, Nickel-Metal Hydride (NiMH), Lithium-Ion (Li-ion) with variants of NMC and LFP and new Solid-State types of batteries is structured.

1. Energy Density and Weight: Energy density has a direct effect on driving range and weight of the vehicle. Lead-acid batteries have extremely low energy density, which means they are heavy and inappropriate to the long-range EVs of today. NiMH batteries have moderate gains and remain below lithium-based systems. Li-ion batteries, especially the NMC chemistry, have high energy density that allows the battery to have a longer driving range with a lower mass. LFP batteries are slightly low in energy density when compared to NMC and still have acceptable performance in urban and commercial use. It is estimated that solid-state batteries outperform standard lithium-ion systems in energy density, possibly creating lightweight and longer-range EVs.

2. Cycle Life and Durability: Cycle life is what

defines battery longevity and cost of lifecycle. Batteries made based on lead-acid deteriorate rapidly and possess a short charge-discharge cycle. NiMH batteries have increased durability but have increased self-discharge rates. Batteries using Lithium-ion are much longer in the cycle life, particularly LFP chemistry, which has a reputation of being extremely durable and stable. Solid-state batteries will also increase the cycle life since there will be less degradation of electrolytes.

3. Thermal Stability and Safety: EV battery systems are important in terms of safety. Lead-acid batteries are non-reactive, but very toxic to the environment. NiMH batteries have a good thermal tolerance. Despite their efficiency, Lithium-ion batteries pose a threat of thermal runaway when not handled well. LFP chemistry is safer because of higher thermal stability and reduced chances of combustion. The use of solid-state batteries removes liquid electrolytes and fire risks are significantly

reduced, which is safer.

4. Sustainability of Cost and Material: Lead-acid batteries are cheap yet dangerous to the environment owing to the presence of lead. NiMH batteries are dependent on rare earth which is costly and a supply issue. Li-ion batteries in most cases NMC, rely on cobalt and nickel, which makes the question of sustainability and ethical sourcing. LFP batteries minimise the use of rare metals, enhance cost stability and environmental friendliness. New technologies of sodium-ion and solid state are supposed to reduce reliance on rare materials even more.

5. Commercial Viability: Today, the EV market is dominated by lithium-ion batteries that have their performance and technological maturity. LFP batteries are getting more popular in the price-sensitive markets and commercial fleets. The solid-state batteries are still in developmental phase and the commercialization requires the manufacturing and scaling challenges to be overcome.

Table 1 Comparative of EV Battery Technologies

Parameter	Lead-Acid[21]	NiMH[22]	Li-ion (NMC/NCA) [23]	Li-ion (LFP)[25]	Solid-State[26]	Sodium-Ion[27]
Energy Density (Wh/kg)	30–50	60–120	180–270	120–200	300–400	100–175
Power Density (W/kg)	80–160	150–450	180–330	180–220	>2500	500-1500
Cycle Life (approx.)	300–500 cycles	500–1000 cycles	1800–2500 cycles	2000–8000 cycles	3000–5000 cycles	500–2000 cycles
Fast-Charge Capability (C-rate)	≤0.3C	~0.5C	1C–3C	1C–4C	1C–2C	>3C
Operating Temp. Range (°C)	–20 to 50	–20 to 60	–20 to 60 (with cooling)	–20 to 65	–20 to 60	–30 to 100*
Charging Speed	Slow	Moderate	Fast	Fast	Very Fast	Moderate-fast
Thermal Safety	Moderate	Good	Moderate	Very high	Very high	High
Cost (\$/kWh)	50-100	120-180	~120–160	~90–110	>\$200	~\$60–90
Environmental Impact	High (lead)	Moderate	Moderate-High	Low	Medium-Low	Very Low
Commercial Adoption	Auxiliary systems	Hybrids	Passenger EVs	Entry/mid EVs	Early (demo/pilot)	Emerging (2025+)

None of the battery technologies meet all the performance, safety, and sustainability requirements. Lithium-ion batteries are still the most viable option to current EV applications with LFP providing greater safety and cost benefits. The development of solid-state and alternative chemistries in the future will solve the current shortcomings and determine the future generation of electric mobility.

Conclusion

The lead-acid batteries cannot be used in the current EVs because of low energy density, high weight and poor cycle life. However, NiMH batteries are more durable than lead-acid but has low energy density and high self-discharge. Based on high energy density, decent power capability and established manufacturing, Li-ion (NMC) batteries take the lead in the modern EV markets. Nevertheless, NMC chemistries have thermal safety, cobalt dependency and cost volatility issues. Li-ion LFP batteries are also more thermally stable, have long cycle life and are less expensive which makes them appealing to mass-market and commercial EV. LFP has the greatest weakness of having a lower energy density than NMC, which influences driving range. Solid-state batteries have the potential of having ultra-high energy density, increased safety and quick charging but they are limited by cost and scalability. Sodium-ion batteries are cheap, sustainable solution because there are plenty of raw materials and have good safety properties. They have lower energy density and are now limited to short-range or entry-level EVs. The future adoption of EVs will depend on optimization in terms of the application and LFP and NMC will be dominant on the short-term and solid-state and sodium-ion will structure the long-term evolution.

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