

Battery Technologies of Electric Vehicles Sustainability: Characteristics, Types, and Charging Techniques

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Received: 7 Jan. 2025, Revised: 21 Apr. 2025, Accepted: 1 June 2025

Published online: 1 Sep. 2025

Abstract: The battery technologies, including design and manufacturing, have undergone significant advancements in recent years to meet the performance requirements of various applications, including the stationary and electromobility sectors. Electric vehicles (EVs), including fuel cell electric vehicles (FCEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs), rely on batteries for their operation. Charging techniques such as Vehicle-to-Everything (V2X), fast charging, and conventional systems are essential for these vehicles. Batteries are increasingly utilized in stationary applications as temporary buffer energy storage solutions for electrical control in micro- and smart grids. This review presents a comprehensive analysis of various battery categories, examines the different battery types, and presents the findings. The discussion covers parameters such as energy storage efficiency, structural features, cost considerations, safety precautions, and operational longevity. Comprehensive comparisons between batteries and charging systems are carried out in this article to assist researchers, engineers, and experts in the fields of EVs and batteries.

Keywords: Electric Vehicles; Energy storage systems; Lead-acid battery; Lithium based battery; Nickel-based battery; ZEBRA battery, Sustainability.

1 Introduction

Two of the biggest issues facing the world's main transportation modes are increasing oil prices and rising carbon emissions. As a result, electric vehicles (EVs) are becoming more well-liked as a means of transportation that has garnered the most attention lately due to their potential to reduce greenhouse gas emissions and dependency on fossil fuels [1,2]. An electric motor that runs on rechargeable batteries powers the engine of an electric car rather than gasoline or diesel. By 2030, three times as many people are expected to use EVs compared to 2011. High-tech developments in battery performance and how they impact vehicle autonomy are the cause of this [3]. Plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and hybrid electric vehicles (HEVs) are the three main categories of electric cars [4]. The propulsion system of each of the three types of EVs is electricity, but their individual powertrains and electric range allow them to function differently. Hybrids can not plug in and recharge from the grid, so they use their

internal combustion engines and regenerative braking systems to recharge their propulsion vehicle batteries [5]. Most hybrid vehicles require the combustion engine to always function to maintain motion; they are not designed to run solely on battery power. Some hybrids, nevertheless, are only able to move the car a few steps at a time before the combustion engine must kick in to help. PHEVs and HEVs primarily differ in that the plug-ins have bigger batteries and can be charged by plugging in. Plug-in electric automobiles can run for a while without the help of a combustion engine because they have larger vehicle batteries [5]. BEVs are a type of EVs that exclusively utilizes chemical energy stored in rechargeable battery packs for propulsion. Unlike other EVs that may incorporate secondary sources of propulsion, such as hydrogen fuel cells or internal combustion engines (ICEs), BEVs employ electric motors and motor controllers instead of ICEs [6]. This means that BEVs derive all their power solely from battery packs, and as a result, they lack internal combustion engines, fuel cells, or fuel tanks. The category of BEVs

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encompasses a wide range of transportation modes, including motorcycles, bicycles, scooters, skateboards, railcars, watercraft, forklifts, buses, trucks, and cars. This broad applicability underscores the versatility and potential of BEVs in promoting sustainable and efficient transportation solutions across various sectors [7]. The challenges facing EVs encompass various aspects, including battery cost, charging time [8], driving range [9], lack of charging infrastructure [9], safety concerns, temperature management [9], and thermal effects [8,9,10,11]. High battery costs, primarily driven by expensive materials like cobalt, nickel, and lithium, have decreased steadily over the last decade. Charging time remains a hurdle, with even rapid charging taking over an hour for a full charge, while the average driving range of EVs, about 350 km, falls short of conventional vehicles. Inadequate charging infrastructure exacerbates "range anxiety" among drivers, necessitating a widespread charging network akin to petrol stations. Safety concerns center around the risk of cell breakdown and explosions, especially in lithium-ion batteries, with thermal management crucial for maintaining battery health and performance. Challenges such as thermal runaway and temperature fluctuations further underline the need for stringent safety measures and design standards. Overall, addressing these challenges is critical for enhancing the adoption and usability of EVs in the automotive industry [12,13].

The late 1920s marked the decline of the market for the first generation of EVs. Unfortunately, battery-powered EVs were still unable to compete with gasoline-powered cars due to their short driving range, long battery recharge times, and lack of charging stations. Aside from these challenges, lead-acid and nickel-cadmium (Ni-Cd) batteries were the only types suitable for EVs in the 1900s [14]. Lead-acid batteries lost market share when EVs started gaining popularity in the mid-1990s due to their low specific energy (30-40 Wh/kg), low energy density (80-100 Wh/L), and limited travel range. Nowadays, lead-acid batteries are predominantly used in electric two-wheelers, forklifts, and e-rickshaws [15]. The lithium-ion battery made its debut in 1991. With high specific energy (120-250 Wh/kg) and energy density (600 Wh/L), it became the market leader in the battery revolution. Lithium-ion batteries are currently the lightest and most durable batteries suitable for EVs. Consequently, lithium-ion batteries started gaining traction as EVs batteries, providing distinct advantages such as long cycle life, large energy capacity, and high efficiency [16]. Nickel-metal hydride (Ni-MH) batteries were used to power hybrid EVs in 1997. Ni-MH batteries were relatively more potent than lead-acid batteries in terms of specific energy (60-120 Wh/kg) and energy density (140-300 Wh/L). Despite certain benefits over lead-acid batteries, Ni-MH also lost the race with the development of Li-based batteries [17]. The range of an EVs depends on various factors, including the type and quantity of batteries used, terrain, weather, and driver performance.

Energy efficiency also impacts battery capacity, with a higher percentage of stored energy correlating with a better battery efficiency rating. A high-efficiency battery charges more quickly and may reach a deeper depletion, making it comparable to a large-capacity battery [14]. Different battery models have varying capacities, as different manufacturers produce them. The battery's efficiency determines how much of its capacity can be charged and discharged. Li-ion battery technology has demonstrated a higher energy density than other EVs batteries, allowing them to run more devices simultaneously for longer periods, store more energy, and discharge more fuel [11,12]. This work aims to identify the characteristics of the battery technology of EVs applications, produce a comprehensive comparison between different charging techniques for the batteries, introduce a comparison between the three different levels: level 1, level 2, and level 3, and carry out a robust comparison between different characteristics of the battery technology.

2 Characteristics of batteries in EVs

Battery performance is defined by several key characteristics that play a crucial role in determining its suitability for various applications. Capacity refers to the amount of electric charge a battery can store, measured in ampere-hours (Ah) or milliampere-hours (mAh). It signifies the total energy a battery can deliver over a single charge-discharge cycle [18]. Energy density is the measure of how much energy a battery can store in its volume or weight. It is expressed in watt-hours per liter (Wh/L) or watt-hours per kilogram (Wh/kg). Higher energy density indicates a more efficient use of space or weight [19]. Specific energy is the energy a battery can deliver per unit of mass, often measured in watt-hours per kilogram (Wh/kg). It provides insights into a battery's efficiency in terms of weight, crucial for applications with weight constraints [20]. Charging cycle life refers to the number of complete charge-discharge cycles a battery can undergo before its capacity significantly degrades. It is a crucial factor in evaluating the longevity and reliability of a battery over time [21,22,23]. Internal resistance is the opposition a battery faces to the flow of electric current during charge and discharge. Lower internal resistance leads to more efficient energy transfer, minimizing heat generation and enhancing overall performance [1]. The effectiveness of a battery encompasses its ability to meet specific application requirements efficiently. It considers factors such as reliability, safety, and cost-effectiveness, considering the intended use and environmental impact [18]. Deep cycling is the process of regularly depleting a battery to a large percentage of its capacity and then recharging it. Deep cycle batteries are usually intended to be discharged to a level of 50 to 80% of their total capacity before being recharged. Deep-cycle batteries are used in applications that require continuous, low-level

power delivery over extended periods. Examples of these applications include naval applications, EVs, solar energy storage systems, and various kinds of UPS (Uninterruptible Power Supply) systems. They have thicker plates and are made to endure several deep discharge cycles without seeing appreciable performance deterioration. A battery that is discharged to a relatively small percentage of its total capacity before being recharged is said to be in a shallow cycle. Shallow cycle batteries typically discharge between 10% to 15% of their total capacity before requiring recharge. These batteries are employed in applications where there is a need for short, high-current discharges followed by rapid recharging, such as automotive starting batteries, certain consumer electronics, and applications requiring occasional brief bursts of high power. They are optimized for quick recharge times and designed to deliver high-power bursts for short durations. Knowing these characteristics makes it easier to choose the right kind of battery for the specific requirements of the application, considering factors like power output, cycle life, and recharge characteristics. The batteries for EVs applications are to be designed to meet the following characteristics: 1) Possess a high energy density: Compared to other battery technologies, they can store a comparatively large amount of electrical energy in a smaller and lighter package. 2) Capable of withstanding low temperatures without deteriorating and performing effectively in high temperatures. 3) Possess a low self-discharge rate, which implies that the battery retains its energy well even after being idle for several days or weeks. 4) Maintain nearly all their initial capacity even after numerous charge cycles. 5) An ideal Battery should be able to operate within a range of temperatures with minimum or no drop in its operating capacity. Based on several factors, Table 1 contrasts different kinds of batteries. At a temperature between -20 and 45 °C, lead-acid batteries provide 30-60 Wh/kg of specific energy, 500-800 cycles, moderate efficiency, and minimal self-discharge. They are considered inexpensive batteries. Despite having a high self-discharge rate of 20%, Ni-Cd batteries offer a moderate energy density and reasonable cycle endurance (2000 cycles). High self-discharge (30%) and a shorter cycle life are two drawbacks of nickel-metal hydride (Ni-MH) batteries, despite their greater specific energy (60-120 Wh/kg). Low cycle durability despite good temperature tolerance characterizes nickel-zinc batteries, which are reasonably priced. With sodium-sulfur cells offering 150 Wh/kg specific energy and ZEBRA (Na/NiCl_2) batteries delivering 160 Wh/kg for cells and 90 Wh/kg for batteries, high-temperature batteries such as these are ideal for specialized applications due to their high cycle endurance and efficiency. The Lithium-ion (Li-Ion) battery is the best type, according to the statistics in the table. It has a wide temperature range (-20 to 60 °C), extended cycle durability (400-3000 cycles), high efficiency (93%), and the highest specific energy (100-275 Wh/kg) and specific

power (350-3000 W/kg). Notwithstanding its greater price, it is perfect for high-performance applications due to its low self-discharge rate of 2-3% per month. Among the listed battery types, it is the most adaptable and efficient due to its overall higher performance metrics in energy density, power, and longevity; therefore, lithium-ion technology is the preferred choice for modern EV batteries across various criteria. Table 2 compares the main types of EVs batteries. Figure 1 presents a comparison of different features of lithium-ion batteries that are utilized in important applications such as electric cars (EVs), solar energy (PV), and other applications (APS). Data for each application is included, including cycle durability, cost, efficiency, specific power, energy density, and cell voltage. Particularly, EVs batteries have the highest specific power and cycle durability, whereas PV and APS batteries are similar but differ in terms of specific power and price. Li-ion batteries demonstrate remarkable versatility and superior performance in Table 3, with specific energy ranging from 100 to 275 Wh/kg and energy density up to 735 Wh/L, especially in EVs applications. They also exhibit high specific power (up to 3000 W/kg for EVs) and consistent cell voltage around 3.6 V. Li-ion batteries are notable for their long cycle durability (up to 3000 cycles), high efficiency (up to 93% in EVs), and low self-discharge rates (as low as 0.35% per month), making them highly efficient and cost-effective. These advantages underscore the suitability of Li-ion batteries for a wide range of applications, providing high energy density, long lifespan, and robust performance in diverse operating conditions.

3 Types of batteries in EVs

Figure 2 presents the different types of BES used in EVs. Table 4 highlights the benefits, drawbacks, and applications of BESs as it compares them. Despite their short life cycle and safety problems, lead-acid batteries are inexpensive, have a low self-discharge rate, and operate well in high temperatures, making them excellent for automotive use and UPS systems [24,25]. Although lithium-ion batteries are expensive, have safety and recycling concerns, and are perfect for high-performance applications like consumer electronics, they excel in energy density and longevity. Previously utilized in consumer devices, nickel metal-hydride (NiMH) batteries are safe and environmentally friendly but have a high self-discharge rate and limited cycle life. Long-lasting and dependable, Ni-Cd batteries are ideal for emergency power and signaling, despite their poor energy density and hazardous cadmium content. Nickel-zinc batteries, with good capacity retention and quick recharge, are used in EVs and deep-cycle applications, but they have a short cycle life and lower energy density [26,27].

Table 1: Characteristics of EVs batteries [18, 19]

Battery type	Pb-PbO ₂	Ni-Cd	Ni-MH	Li-ion	Nickel-zinc	Sodium-sulfur	ZEBRA (Na/NiCl ₂)	Na-NiCl ₂
Working Temp. (°C)	-20–45	0–50	0–50	-20–60	-30–75	NR	270–350	250–350
Specific Energy (Wh/kg)	30–60	60–80	60–120	100–275	75	NR	160 (cell)	90 (battery), 86
Energy Density (Wh/L)	60–100	60–150	100–300	200–735	NR	150	NR	149
Specific Power (W/kg)	75–100	120–150	250–1000	350–3000	500	150	150	150
Cell Voltage (V)	2.1	1.35	1.35	3.6	1.65	NR	2.67	NR
Cycle Durability	500–800	2000	500	400–3000	500	NR	2000	2500–3000
Cost (USD/kWh)	100	300	853–1500	600–1000	90–120	NR	NR	160–300
Efficiency (%)	80	70	75	93	70	80–90	90	80
Self-discharge (%/month)	3–5	10	10–15	1–2	10–20	20–30	1–3	1–3
Depth of Discharge	Shallow	Deep	Deep	Deep	Shallow	Deep	Deep	Deep

Table 2: The comparison of the types of electric car batteries

	Li-ion	Ni-MH	Lead-acid
Easy Access	✓	×	✓
Energy Efficient	✓	✓	✓
Temp. performance	✓	×	×
Weight	✓	✓	✓
Life Cycle	✓	×	✓

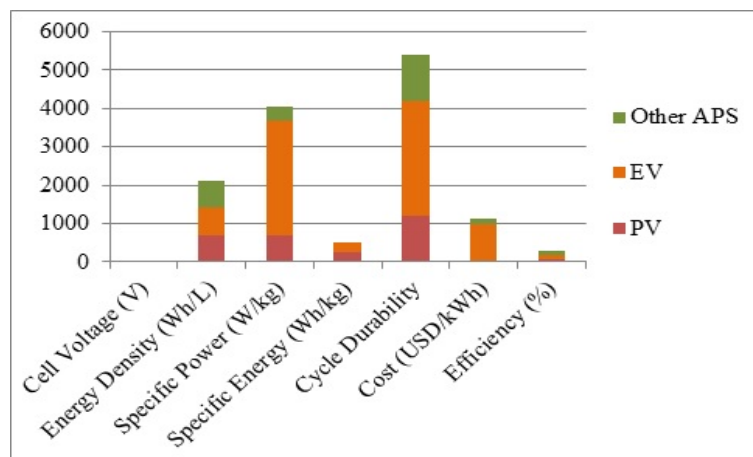
**Fig. 1:** Comparison between Li-ion batteries used in different applications.

Table 3: Comparison of Li-ion batteries used in different applications.

Battery Type	PVs	EVs	Other Applications
Working Temp (°C)	−20-60	−20-60	NR
Specific Energy (Wh/kg)	170-250	100-275	100-265
Energy Density (Wh/L)	250-693	200-735	250-693
Specific Power (W/kg)	250-693	350-3000	250-340
Cell Voltage (V)	3.6 / 3.85	3.6	3.6 / 3.7 / 3.8 / 3.85
Cycle Durability	400-1200	400-3000	400-1200
Cost (USD/kWh)	High	600-1000	132
Efficiency (%)	80-90	93	80-90
Self-discharge per month (%)	<10	2-3	0.35-2.5

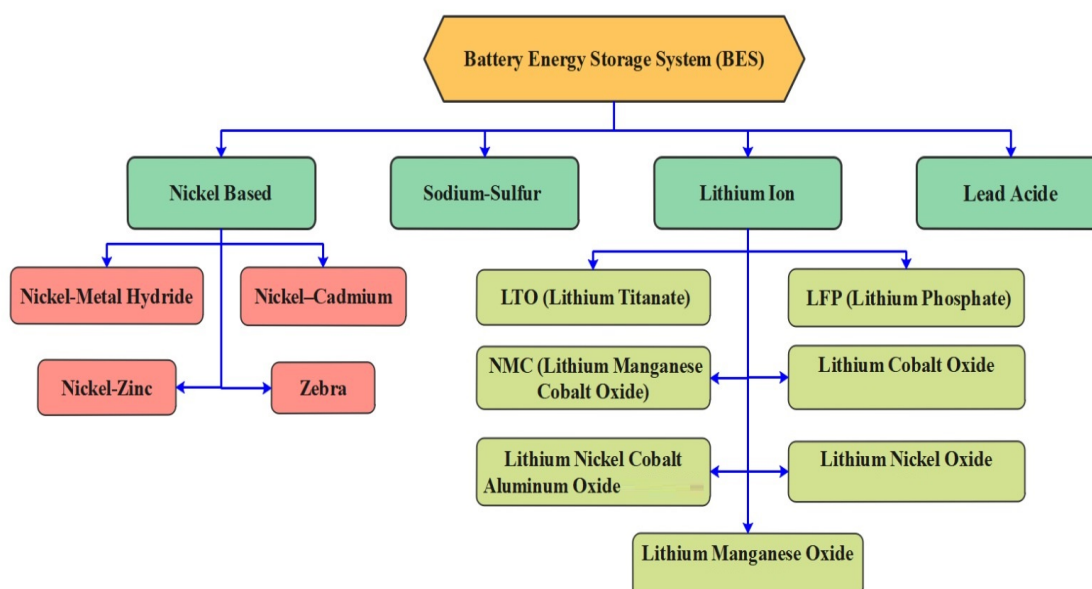
**Fig. 2:** Types of battery energy storage systems.

Table 4: Advantages and disadvantages of different battery systems

Battery Type	Advantages	Disadvantages	Application Examples
Lead-acid [9,20,21]	–Advanced technology –Minimal material expenditure –Minimal rate of self-discharge –Reasonably cheap initial outlay –Effective in hot and cold conditions	–Limited life cycle –Moderate power and energy density –Gas leak safety concerns –Sensitive to temperature output –Lack of dependability	–Distributed power, renewable energy, UPS –SLI batteries for cars –Emergency lighting, power tools, phones –Mining and material-handling machinery
Lithium-ion [8,9]	–Extended life cycle –Excellent round-trip performance –Superior energy and power density –Lightweight	–Exorbitant initial investment –Safety concerns (thermal runaway) –Subpar recycling and recovery –Sensitive to high temperatures	–High-performance energy/size-critical use –Laptops, cell phones, media players –Aerospace, automotive, military research
Nickel-metal hydride [22,23]	–Reasonable starting price –Moderate round-trip efficiency –Outstanding safety record –Eco-friendly substances	–Elevated self-discharge rate –Memory effect –Brief cycle life –Inadequate recycling/recovery	–Former use in laptops and mobile phones
Nickel-cadmium [24,25]	–Relatively cheap –Superior cycle life –Excellent safety record	–Low power/energy density –Memory effect –Low round-trip efficiency –Cadmium toxicity	–Emergency power, traction, rail signaling –Communication and standby power –Traffic and power distribution systems
Nickel-Zinc [28,29]	–Competitive capacity retention –Wide temperature range –Quick recharge –Sealed, no maintenance	–Short cycle life –Lower volumetric energy density	–E-scooters, e-bikes, EVs, HEVs –Deep-cycle: wheelchairs, golf carts –Lawnmowers, trolling motors

3.1 Lead-acid batteries

Gaston Planté pioneered the first rechargeable traction battery 160 years ago, refined and introduced in 1886 [30, 31], utilizing spongy lead, lead oxide, and sulfuric acid. Enhanced lead grid lattice implementation over time increased the battery's strength. Despite applications in submarines, EVs, and sump pump power generation, lead-acid batteries face drawbacks such as high weight, low power density, and a short life cycle, although they still contribute significantly to the automotive industry due to their low cost and widespread availability [32,33]. Noteworthy features include a substantial power-to-weight ratio and the ability to supply strong surge currents. Because lead-acid batteries don't have a memory effect, they need exact charge and float voltages to keep the electrodes from deteriorating over time. Lead-acid batteries with deep cycles can withstand up to 300 charging cycles on average. Three stages of charging are used: the constant-current bulk charge provides most of the charge, followed by the float charge and the equalization final charge. Undercharged batteries from extended unplugged times are addressed by overcharging or active charging, whereas the float charge makes up for such situations. Uniform cell charging is ensured by the equalizing charge [34].

3.2 Lithium-ion batteries

With features like low weight, high energy density, and rechargeability, lithium-ion batteries that can be recharged have become a game-changer in technology. Particularly in the automotive industry, lithium-ion batteries are extensively used and rapidly evolving in the field of e-mobility [35,36]. They are acknowledged as a noteworthy innovation in the field of electrochemistry. Because these batteries use an electrolyte made of lithium salt mixed in an organic solvent [37,38,39], with metal oxide acting as the cathode and carbon as the anode, they provide significant specific energy and mileage gains over lead-acid batteries. Although there are some drawbacks, such as high manufacturing costs and aging, the technology is favored for its low self-discharge, low maintenance requirements, long life cycle, high energy capacity, and overall performance, expanding its applicability to portable gadgets and airplanes. Lithium-ion batteries are expected to be progressively incorporated into established markets and the everyday lives of individuals due to ongoing technological improvements [40].

3.2.1 Lithium cobalt oxide

The lithium cobalt oxide battery was created by Sony in 1991, and since then, it has become the standard battery for the majority of personal devices, including laptops,

cameras, tablets, and so on, because of its high energy density, lengthy lifespan, and ease of manufacture [41]. Since they have low thermal stability due to their high reactivity, lithium cobalt batteries need to be closely watched while in use to guarantee safety. Moreover, cobalt's restricted supply makes it more costly and challenging to be a practical choice for EVs use. However, this high energy density battery powers the smart for two electric drive and the Tesla Roadster.

3.2.2 Lithium nickel oxide

An important development in energy storage technology is represented by lithium nickel oxide (LiNiO_2) batteries. Due to their exceptional thermal stability and high energy density, these batteries are well-suited for a wide range of applications, including portable devices and EVs [42]. In addition to providing better safety features than conventional lithium-ion batteries, the cathode material, LiNiO_2 , enables a larger capacity and longer cycle life. lithium nickel oxide batteries will remain essential for powering modern devices and transportation in the future as demand for efficient and sustainable energy solutions rises [43].

3.2.3 Lithium manganese oxide

Lithium manganese oxide (LMO) batteries were first introduced in the early 1980s, but it took more than 15 years for them to be commercially available [44]. The construction lowers internal resistance and improves current control by enhancing ion flow on the electrode and forming a three-dimensional spinel structure. Low internal cell resistance allows for both rapid charging and high-current discharging [45]. Li-manganese with a moderate build-up of heat can be discharged at currents of 20-30 A in an 18,650 package. This chemistry provides better thermal stability than lithium cobalt oxide batteries, but the cost is a roughly 33% reduction in capacity and a shorter lifespan. Lithium manganese cobalt oxide (NMC) is blended into most Li-manganese batteries to increase specific energy and extend life. EVs manufacturers Nissan Leaf, Chevy Volt, and BMW i3 are among those that have previously employed the LMO-NMC [46].

3.2.4 Lithium nickel cobalt aluminum oxide

Applications for lithium nickel cobalt aluminum oxide (NCA) date back to 1999. It is comparable to NMC in that it offers a long life length along with high specific energy and specific power (the rate at which the battery can deliver energy) [41]. Extra safety precautions must be taken while utilizing NCA in EVs because it is less safe than the other materials indicated above [33]. They are also less feasible for use in other applications because of

their greater manufacturing costs. Since they are the only EVs manufacturer currently using NCA chemistry, Tesla claims that its NCA battery in production contains even less cobalt than NMC811. There was only 15% cobalt in the NCA batteries used in the 2012 Tesla Model 3 and Model S [47].

3.2.5 Lithium manganese cobalt oxide

NMC batteries function well generally because of their high specific energy, high power, and low self-heating rate. In this system, graphite acts as the anode, and LiNiMnCoO_2 as the cathode. Batteries are also widely used in e-bikes, electric power tools, and other powertrains due to their low cost and lightweight nature [41]. The fact that regular EVs use require a 6-hour charging period and that the battery's optimal performance is dependent on the surrounding temperature remaining below 40° are the battery's limitations. The average battery discharge rate is two hours, with a maximum depth of discharge of 80% and a maximum lifespan of 2500 charging cycles.

3.2.6 Lithium titanate

Compared to NMC batteries, lithium titanate (LTO) batteries exhibit more potential. The battery technology's two most remarkable attributes are its shorter charging times and its tolerance for 45°C ambient temperatures. It is also widely used for solar-powered lighting, transportation, home energy storage, and other applications due to its 10,000 life cycles. However, its poor specific energy, three to four times higher costs than the NMC, and large weight are its significant drawbacks [48]. Honda uses titanate batteries in the Fit EV, and Mitsubishi uses them in some Japanese-only i-MiEVs models. LTO is also utilized by the Tosa concept electric bus [49]. Because of their exceptional level of safety, lithium titanate batteries are used in portable medical equipment [50].

3.2.7 Lithium phosphate

Among the safest batteries are LFP batteries because of their exceptional capacity to withstand high temperatures with little to no deterioration. The LFP batteries occupy an intermediate position between the NMC and LTO batteries due to their superior load and unload capacity and higher, albeit lower, temperature tolerance than the LTO batteries. It also has an excellent calendar life and a reduced rate of capacity decline [51].

3.3 Nickel-based batteries

3.3.1 Nickel-metal hydride battery

One of the most widely accessible rechargeable battery types is nickel-metal hydride, which uses titanium or nickel as the negative electrode and nickel hydroxide as the positive electrode. Alkaline solutions, often potassium hydroxide, are used as electrolyte solutions. These batteries have a long lifespan, can withstand a large temperature range, are recyclable, and are resistant to mild poisons. However, they are inoperable in devices that operate on primary alkaline chemistry, have decreased self-discharge, and have decreased capacity due to voltage depression [52].

3.3.2 Nickel-cadmium batteries

In Ni-Cd batteries, an alkali solution acts as the electrolyte, and nickel and cadmium species as the positive and negative electrodes. This proven technology has been in use since 1950 due to its long life cycle (more than 3500) and low maintenance needs. The Ni-Cd battery has a low internal resistance and a high degree of discharge period in a comparatively short amount of time. For it to operate well during service, a high charging rate at a fast cycle is required. The two main problems with Ni-Cd batteries are cadmium toxicity and the ensuing inefficiency of the metal for the environment [53].

3.3.3 Zebra battery technology

An innovative technology that was first created in South Africa in the 1970s and 1980s is the ZEBRA (Sodium Nickel Chloride) battery, which is now produced in Switzerland for use in EVs applications [54]. The ZEBRA battery, which has a cycle life that is 7-8 times longer than lead-acid batteries, operates without maintenance and is well-known for its durability and variety of configuration possibilities designed specifically for EVs. With its low tolerance for cell failure, linked chains of cells can continue to function even if a few cells stop working. Some benefits are that it is robust, economical, adaptable to different room temperatures, produces no gas emissions, has a low self-discharge, and is easy to estimate charged [55]. However, a notable drawback is its slow thawing time of 12 to 15 hours after freezing, along with an energy loss of 90 watts when idle.

3.3.4 Nickel-zinc batteries

In terms of rechargeable battery technology, nickel-zinc (Ni-Zn) batteries are a viable substitute that is especially useful for power tools and high-drain applications. Compared to other nickel-based chemistries, these

batteries are renowned for having a high energy-to-mass ratio and being comparatively less expensive. Zinc functions as the negative electrode and nickel hydroxide as the positive electrode in a Ni-Zn battery. Both electrodes are submerged in an alkaline electrolyte, such as potassium hydroxide (KOH). This chemistry has advantages over nickel-metal hydride batteries, including nonflammability, quick recharge times, high discharge rates that preserve thermal stability, and ease of recycling without sacrificing the battery's physical or chemical integrity [56]. Widespread commercialization attempts are still hindered by obstacles including gas recombination in sealed cells, the possibility of short circuits, and worries over battery lifespan.

3.4 Sodium batteries

Because sodium batteries have the potential to solve the shortcomings of existing energy storage technologies, they represent a promising improvement in battery technology. Because sodium is more abundant than lithium in the Earth's crust and ocean, it is also less expensive to harvest for use in batteries [57]. This is one of the key benefits of sodium batteries. These batteries are next-generation alternatives ready to take the place of current technologies since they make use of solid-state electrolytes [58]. Because these batteries use sodium as the active material, they provide a sustainable alternative that may have less of an impact on the environment. There are still issues with performance and longevity, but research and development efforts are being directed toward finding solutions so that sodium batteries can be widely used in a variety of applications, such as portable devices and grid storage.

3.4.1 Sodium-sulfur

A state-of-the-art energy storage technology renowned for its high energy density and affordability is the sodium-sulfur (Na-S) battery. The way this cutting-edge technology works is that a solid electrolyte separates the solid anode, which is molten sodium, from the solid cathode, which is a composite made of sulfur. Even though it must operate at a high temperature, typically around 300 °C, which poses problems for material durability and safety, continuous research efforts are meant to improve its effectiveness and dependability. Applications needing large energy storage capacities, such as load leveling, grid-level electricity storage, and backup power systems for vital infrastructure, are areas where Na-S batteries have tremendous promise. Na-S batteries have enormous potential to transform industrial and renewable energy applications as long as efforts are made to enable them to function efficiently at room temperature [59].

4 Batteries charging techniques

Battery life cycles and performance can be greatly extended by using proper charging procedures. Therefore, several criteria are considered, including quick charging, high-quality charging current, and avoiding under and overcharging. Specifically, overcharging a battery can harm its physical components, whereas undercharging can lower its energy density. As a result, the charging process should use an appropriate control method. The key characteristics of the various charging methods are compiled in Table 5 and Fig. 3.

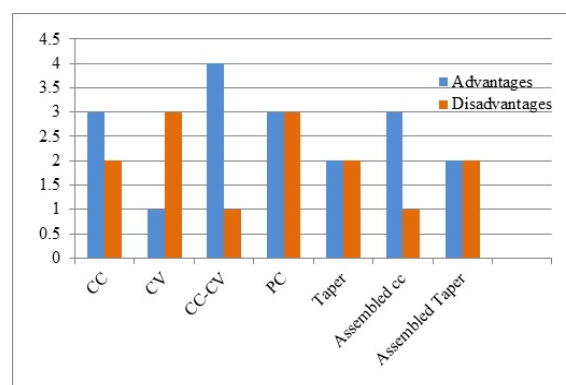


Fig. 3: Comparison between different charging techniques.

Different battery charging methods are shown in Table 5, along with their benefits and drawbacks. Implementing constant current (CC) charging is straightforward and uncomplicated; however, using high currents runs the risk of overcharging, while using low currents prolongs the charging duration. Though it prolongs charging with low current at the end, constant voltage (CV) is likewise simple to apply, but it raises battery temperature initially. Though it requires quick control loops and high-bandwidth sensors, pulse current charging maximizes battery life and charging speeds at a high cost. Though difficult to install and needing closed-loop control with both sensors, the taper characteristic method offers steady current reduction and overcharging protection. Combining the advantages of continuous current charging with its disadvantages, both constant current and taper characteristic approaches require more intricate control strategies. The constant current-constant voltage (CC-CV) method is the most effective charging strategy. By combining the benefits of constant voltage and constant current charging, this technique prevents overcharging and current surges while providing outstanding performance. It offers a balanced approach to effective and secure battery charging by permitting float charging once the battery is fully charged. While it necessitates both voltage and current sensors for closed-loop control, its extensive advantages make it the best option out of the strategies mentioned.

Table 5: Comparison between different charging techniques.

Charging Technique	Advantages	Disadvantages
Constant Current [51,52]	–First-order open-loop transfer function –Controller simplicity –Easy implementation	–Risk of overcharging with high current –Longer charging time with low current
Constant Voltage [52,53]	–Simple to implement	–Increased battery temperature during initial charging –Extended charge time due to low current in the final phase –Second-order open-loop transfer function
Constant Current-Constant Voltage [60]	–Prevents overcharging –No current surge during charging –Excellent performance –Supports float charging after full charge	–Requires both current and voltage sensors for closed-loop control
Pulse Current	–Extends battery life through optimized chemical behavior –Adjustable charge rate via duty cycle –Even ion dispersion in electrodes	–Requires a fast control loop –Needs a high-bandwidth current sensor –Expensive
Taper Characteristic	–Gradual current reduction during charge –Protection from overcharging	–Complex implementation –Requires both voltage and current sensors
Assembled Constant Current	–Avoids overcharging (unlike basic CC) –Avoids excessive charge time –Retains CC benefits	–More complex control than CC
Assembled Taper Characteristic	–Customizable charge curve for different designs –Improved charge performance	–Most complex control method –Requires both voltage and current sensors

4.1 EVs charging stations

Reliable and secure choices for recharging, along with a sufficiently spread infrastructure, are necessary to meet customer needs and encourage the use of EVs, especially considering the rapid expansion of the market and the increasing battery capacity of these vehicles. Thus, inductive charging (IC) [18,19,56,57], conductive charging (CC) [58,59], and battery swapping (BS) [22,23,61,62] are the three primary categories into which EVs charging technologies can be divided, as shown in Fig. 4 and Table 6.

4.2 Inductive charging

The charging technique utilizes electromagnetic fields for energy transfer without physical contact. Inductive charging comprises a charging pad on the ground and a receiving pad on the vehicle, facilitating wireless energy transfer through electromagnetic induction [18,19]. However, its efficiency is moderate, primarily due to energy losses during the wireless transfer process. The infrastructure necessitates dedicated charging pads embedded in the ground. This method can be applied across different charging levels, encompassing Level 1, Level 2, and potentially Level 3 [56,57,61,62]. Nevertheless, the charging duration is typically slower compared to CC methods.

4.3 Conductive charging

The charging technique involves direct physical contact between the charging equipment and the vehicle. CC employs charging cables and connectors to transmit electricity from the charging station to the vehicle's charging port [63]. It is generally more efficient than inductive charging as it involves direct electrical contact. The infrastructure for CC necessitates charging stations equipped with cables and connectors. This method is versatile and implemented across all charging levels, including Level 1, Level 2, and Level 3. The charging duration varies based on the charging level and power output. Both IC and CC can be applied across various charging levels, with IC requiring dedicated charging pads and generally slower charging durations [64,65].

4.4 Battery swapping

The charging technique of BS involves the replacement of a depleted battery with a fully charged one. Battery swap stations enable users to exchange their empty batteries for fully charged ones, leading to a significant reduction in charging time [22,23]. This method can be highly efficient as it eliminates the need for traditional charging

time. However, it requires specialized battery swap stations equipped with automated equipment [66,67,68,69,70,71]. BS operates independently of traditional charging levels, offering a unique approach to fast charging. The charging duration for this method is extremely fast, typically taking only a few minutes for a full battery swap [72,73].

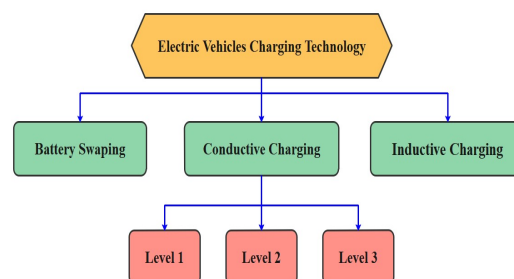


Fig. 4: EVs charging technology.

Three primary EVs charging levels are compared in detail in Table 6: Level 1, Level 2, and Level 3 (DC Fast Charging). Level 1 requires 8 to 20 hours to fully charge, although it can run at 120 volts AC with a charging current of 8 to 12 amperes, giving 1-2 kW of power. This means that it is appropriate for overnight home charging. With 3.3 kW to 22 kW of power and a 240 V, AC working range of 16 to 80 A, Level 2 is perfect for both residential and commercial settings and drastically reduces the charging time to 4-8 hours. Level 3 is ideal for fast recharges on highways since it uses high voltage DC, with currents frequently reaching 100 A, to provide 25 kW to 350 kW of power and charge up to 80% in 30 minutes. Level 3 is exclusive to CC, while Levels 1 and 2 can use inductive, CC, and battery swaps. These several levels are beneficial to EVs, including PHEVs and BEVs; Level 3 helps to reduce range anxiety on lengthy trips.

5 Batteries sustainability

The transition to electric vehicles (EVs) is a crucial step towards a more sustainable future, significantly reducing greenhouse gas emissions compared to traditional internal combustion engine vehicles. Central to this shift is the use of batteries, particularly lithium-ion batteries, which offer a cleaner and more efficient energy storage solution. By enabling the widespread adoption of EVs, these batteries play a pivotal role in mitigating the adverse environmental impacts associated with fossil fuel consumption. Electric vehicles, powered by batteries, produce zero tailpipe emissions, which is a substantial improvement over conventional vehicles that emit large quantities of carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter. The widespread adoption of EVs can significantly decrease urban air pollution, improving air quality and public health. Furthermore, as

Table 6: Comparison between the CC, inductive charging, and BS methods

Power Levels	Level 1 [70,71,72,73]	Level 2 [56,57]	Level 3 (DC Fast Charging) [74,75,76]
Voltage	120 V (AC)	240 V (AC)	High voltage with direct current (DC)
Charging Current	Typically 8-12 A for residential charging	16-80 A (common values: 16, 32, 40 A)	Often exceeds 100 A (e.g., 150, 200, 350 A)
Power Output	1-2 kW	3.3-22 kW	25-350 kW
Charging Duration	Slow: 8-20 hours for full charge	Moderate: 4-8 hours for full charge	Fast: 80% charge in 30 minutes or less
Infrastructure	Standard household outlet	Dedicated charging stations with proper infrastructure	Advanced high-power infrastructure
Applications	Overnight home charging or when time is flexible	Residential/commercial use (workplaces, malls)	Highway quick charging, long-distance travel
Range Anxiety	May contribute due to slow charging	Reduces range anxiety vs. Level 1	Minimizes range anxiety; suitable for trips
Charging Technique	IC, CC, BS	IC, CC, BS	CC
Electric Vehicles (EVs)	PHEVs, BEVs	PHEVs, BEVs	BEVs

the electricity grid becomes greener with more renewable energy sources like wind, solar, and hydro, the overall lifecycle emissions of EVs will continue to decline. This synergy between renewable energy and electric vehicles creates a positive feedback loop, enhancing the sustainability of both technologies. Despite their environmental benefits, the production and disposal of batteries pose significant challenges. Battery manufacturing requires substantial amounts of raw

materials, such as lithium, cobalt, nickel, and manganese, which are often extracted through mining processes that can be environmentally damaging. To address these concerns, the recycling and reuse of batteries have become essential components of a sustainable battery lifecycle. Recycling batteries involves several steps: collection, disassembly, material recovery, and reprocessing [77,78,79,80,81]. Once a battery reaches the end of its useful life in a vehicle, it can be collected and transported to a recycling facility. Here, the battery is disassembled, and its components are separated. Valuable materials such as lithium, cobalt, nickel, and copper are then recovered through various chemical and mechanical processes. These recovered materials can be used to manufacture new batteries, reducing the need for virgin raw materials and minimizing the environmental impact of mining activities. Moreover, batteries that are no longer suitable for vehicle use can be repurposed for secondary applications, such as stationary energy storage systems. These systems can store renewable energy generated during periods of low demand and release it during peak usage times, further stabilizing the grid and enhancing the overall efficiency of renewable energy sources. By extending the lifecycle of batteries through reuse in secondary applications, we can significantly reduce waste and maximize the value derived from each battery. Innovations in battery technology are continuously evolving, aiming to improve the sustainability of batteries from production to end-of-life. Researchers are exploring alternative materials and chemistries that are less reliant on scarce and environmentally damaging resources. Solid-state batteries, for example, promise higher energy densities and improved safety while reducing the need for critical materials. In addition, advancements in recycling technologies are making the process more efficient and cost-effective. Emerging methods, such as direct recycling, which preserves the structure of the cathode materials, can potentially reduce the energy and resource requirements of recycling processes.

6 Conclusion

In conclusion, this article provides a comprehensive analysis of various energy storage technologies and their applications, particularly focusing on electric vehicles. It highlights ongoing efforts to enhance battery performance, aiming to create a more efficient and sustainable energy landscape. It is found that electric vehicles face early challenges, and there is a rise in lithium-ion batteries due to their superior energy density and efficiency. With their low weight, high energy density, and rechargeability, lithium-ion batteries have revolutionized technology, particularly in the automotive industry, where their significant specific energy and mileage gains, along with low self-discharge, long life cycle, and high performance, make them a preferred choice despite high manufacturing costs and aging

concerns. The constant current-constant voltage method emerges as the most effective battery charging strategy, combining the benefits of constant voltage and constant current charging to prevent overcharging and current surges, thereby providing excellent performance and a balanced approach to efficient and secure battery charging. Ultimately, the work underscores the critical role of advancing battery technologies to foster the adoption and success of electric vehicles in the automotive industry. Batteries are at the heart of the sustainable transformation in the transportation sector, significantly reducing vehicle emissions and paving the way for a greener future. Through effective recycling and reuse strategies, we can address the environmental challenges associated with battery production and disposal, ensuring that the benefits of electric vehicles are maximized while minimizing their ecological footprint. As technology and infrastructure continue to advance, the role of batteries in promoting sustainability will only grow, driving us towards a cleaner, more sustainable world.

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