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Comparison of Battery Chemistries for Electric Vehicle Applications

Mostafa Almadani, Oluwafemi Emmanuel Oni, and Omowunmi Mary Longe
Department of Electrical and Electronic Engineering Science
Faculty of Engineering & the Built Environment
University of Johannesburg
Johannesburg, South Africa
222241561@student.uj.ac.za, 223248712@student.uj.ac.za,
omowunmil@uj.ac.za

Lanre Olatomiwa
Department of Electrical and Electronic Engineering Science
Federal University of Technology Minna, P.M.B. 65, Minna, Nigeria
University of Johannesburg, Johannesburg 2006, South Africa
Email: olatomiwa.l@futminna.edu.ng

Abstract

One of the most effective technologies for green and environmentally friendly transportation systems is the electric vehicle (EV). For all battery-driven electric vehicles, the secondary (rechargeable) battery is the main source of energy. Batteries store chemical energy and convert it into electrical energy, then it delivers as electrical energy. The energy storage system is the most important for the long-term economic and ecological sustainability of EVs in the automotive sector. Battery is the central and core component of battery driven EVs. It is the heart of the EVs. It is important to choose batteries that have a long cycle life, less energy loss, high power density, stable and high peak power output, high energy efficiency, lightweight, low maintenance, long-lasting durability, adequate safety, reliable performance, fast charging capability, inexpensive and eco-friendly materials. EVs use various types of rechargeable batteries, including Nickel-Cadmium (NiCd), Lead acid (PbO2), Nickel-Metal Hydride (NiMH), Sodium-Sulfur (NaS), Lithium-Ion (Li-ion), and novel-based batteries. Novel-based batteries, such as Lithium-Sulfur (LiS), Lithium-ion Air (LiO2), All-Solid-State Batteries (ASSB), Zinc-Ion (Zn-ion), Lithium-Ion Silicon (Li-Si), and Sodium-Ion (Na-ion) batteries are currently underdeveloped but have the potential for the next generation of energy storage technology. In this paper, the emphasis is on the various kinds of batteries currently available in the market. Also, battery chemistry application, formation, and comparison of benefits and drawbacks are discussed. A smart energy storage system is very important for green transport systems. Considering all the determining parameters, recommendations for application-specific optimal battery technology for EV applications are presented.

Keywords
Electric Vehicle (EV), Green Transportation, Lithium-Ion (Li-ion) Battery, All-Solid-State Battery (ASSB), Sodium-Sulfur (Na-S) Battery, Battery Chemistry.

1. Introduction
Vehicles are considered the main elements of daily life for personal mobility, and transportation of goods. Most public and private vehicles run on Internal Combustion Engines (ICEs), which are the main cause of air pollution

(Lachvajderová & Kádárová 2021). According to research, fossil fuel emissions are considered one of the main contributors to global warming, climate change, and greenhouse gas (GHG) emissions *(J. Zhao et al. 2021)*. The transport sector is estimated to account for 14% of total GHG emissions from fossil fuels worldwide *(Moustakas, Loizidou, Rehan, & Nizami 2020)*. Many countries worldwide have committed to reducing emissions from their transport sector *(R. Lee & Brown 2021)*.

In the transportation sector, ICE vehicle is a significant contributor to climate change, with 23% of greenhouse gas (GHG) emissions in the atmosphere originating from the transportation sector, and the second largest contributor is the industry sector. As a result, the "Paris Declaration on Electric Mobility and Climate Change and Call to Action" was adopted in 2015. This declaration's major objective is to reduce global warming by over 2 degrees by 2030. If electric vehicles (EVs) represent 35% of total vehicle sales by 2030, this goal can be achieved *(Rivera et al. 2021)*. One of the most efficient and practical approaches to reducing GHG emissions is to switch to EVs from conventional ICE vehicles *(Sopha, Purnamasari, & Ma'mun2022)*. According to reports, a country's GHG emissions might be reduced by 40% if all ICE vehicles were converted to EVs and their charging energy only come exclusively from renewable sources *(Sanguesa, Torres-Sanz, Garrido, Martinez, & Marquez-Barja, 2021)*. Due to reduce air pollution and oil dependence in the transportation sector, the overall use of EVs in the market has increased in recent years. EVs have made significant progress as an alternative to diesel or gasoline-powered vehicles and thus less susceptible to high oil prices. EVs get energy from fuel cells, batteries, and ultracapacitors.

In EVs, rechargeable batteries are frequently used as a mainstream technology for economically affordable and secure energy storage *(Goop, Nyholm, Odenberger, & Johnsson 2021)*. The use of EVs provides a quieter and cleaner atmosphere, and significantly reduces operating costs compared to fossil fuel vehicles. The transport zone requires flexibility and better performance advantages suitable for EVs *(T. Chen et al. 2020; Hemavathi & Shinisha, 2022)*.
Battery technology is one of the key components of electric vehicles (EVs). Many countries, including the USA, Germany, and Japan have started special projects to improve the performance of batteries that can satisfy the requirements of EVs. Year after year, the performance of the battery cell improves significantly *(Rietmann, Hügler, & Lieven 2020)*. In the several research that have been done, various battery technologies have been developed and implemented. This procedure is still ongoing to achieve the desired performance and goals. Today, the battery is the most costly part of an electric vehicle, accounting for 25% to 50% of the total cost of the electric vehicle, depending on the technology utilized *(L. Chen et al. 2019)*. Although battery is a common energy storage tool, the problems are low energy density, high production costs, and safety issues that must be resolved *(Rawdah, Ali, & Hasan, 2021)*. Industries and researchers have been offering to consumers different types of batteries with different characteristics but could not invent any type of battery that has all the good quality, therefore a need for comparison of battery chemistries for EV applications.

The research work reviews current battery chemistry technology and its application in the EV industry. Further observation from this work shows that the future of any good batteries should possess these qualities of long life, less energy loss, high energy density, stable output, high energy capacity, high peak power output, high energy efficiency, maintenance-free, less weight, more durable, high level of safety, reliable operation, good charge retention, fast recharging capability, made of inexpensive and eco-friendly materials and efficient material recovery. And thus can foster the quick deployments of a large-scale battery-driven electric vehicle market *(Shaukat et al. 2018)*.
The rest of the paper is organized as follows: An overview of the EV is described in section II. The concept of battery is presented in section III. In section IV, the chemistry of the different types of batteries is discussed. The comparison of several batteries is described in section V. And the conclusions are emphasized in section VI.

2. Overview of Electric Vehicles

In order to reduce global warming, air pollution, the greenhouse effect, environmental protection, and the oil depletion problem, it is necessary to have suitable and sustainable means of transport as an alternative to ICE vehicles *(Ahuja, Dawson, & Lee, 2020)*. One of the alternative options is electric vehicles (EVs), which have either highly efficient or contribute less to the above problems than conventional vehicles *(Sanguesa et al. 2021)*. An EV is a vehicle that is propelled by one or more electric motors instead of an internal combustion engine (ICE). Can also be described as a vehicle partially or fully powered by electric power. Although, by definition, trains, ships, or aircrafts can be classified as electric vehicles. However, most commonly EVs refer to road vehicles, such as electric cars, bicycles, buses, and trucks *(İnci, Büyük, Demir, & İlbey 2021)*.

EVs are classified into two categories as Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs). According to engine technology, in general, EVs can be categorized into five main types of EVs, they are: Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Fuel Cell Electric Vehicles (FCEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Extended-Range Electric Vehicles (ER-EVs) *(Sanguesa et al. 2021)*.

3. Battery Concept

A battery is a chemical device that stores chemical energy and produces electrical energy. In 1800, Alessandro Volta, an Italian scientist, invented the first battery *(Kim, Oh, & Lee, 2019)*. There are two types of batteries: i). Primary (non-rechargeable) and ii). Secondary (rechargeable) battery. A primary battery provides energy only once when it is discharged. And the secondary battery provides stored energy cyclically (charge and discharge) until the end of its life. Secondary batteries are usually used in EVs. In a secondary battery, electrical energy converts into chemical energy (during charge time) and chemical energy converts into electrical energy (during discharge time) through electron donating (oxidation) and electron-accepting (reduction). A redox reaction occurs when a reaction like this occurs between the positive and negative electrodes *(Hemavathi & Shinisha, 2022)*, *(Dhameja, 2001)*. A battery's "cell" is the component that stores electrochemical energy inside the battery. In a battery, in order to get the desired voltage or current one or more cells are accumulated in series or parallel.

A battery is made up of three main components such as anode, cathode, and electrolyte. The negative electrode, or anode, donates electrons to the external circuit. The positive electrode, or cathode, is capable to collect electrons from the external circuit. The electrolyte is a substance when ions are transferred from the anode to the cathode, they pass through an electrolyte.

Anode (negatively charged electrode): An electrochemical process on the battery cell, oxidation releases electrons that are referred to as the cathode. Battery performance depends on the selection of anode materials. Anode materials should be high specific capacity, stability, efficiency, conductivity, cost, and simplicity of production to maximize battery performance. The cathode (positively charged electrode is an electrochemical reaction that happens on the battery cell, at this electrode reduction process occurs. Electrons are transferred from the anode to the cathode. Suitable cathode materials for batteries are selected based on chemical stability and voltage. Electrolyte: In a battery cell, when an electrochemical reaction occurs, the electrolyte acts as a medium for moving ions and charges between the anode and the cathode. Water or a solvent/dissolved salt can be used as the electrolyte material, which can be liquid, solid, or gel. Electrolytic materials are chosen based on their non-reactivity with electrode materials, high electrical conductivity, thermal stability, safety, and cost *(Hemavathi & Shinisha 2022)*, *(Yuan, Liu, & Zhang 2011)*.
The difference between the anode and cathode voltages depends on the cell's voltage. The combinations of cathode and anode materials depend on the maximum cell capacitance and voltage. In actuality, separators are utilized in cell designs to offer mechanical isolation between the anode and cathode.

3.1 Various Parameters of the Battery

The battery of an electric vehicle must have certain characteristics for the effective and smooth operation of the EVs. These are few of the features of EV batteries.

- Stable Output: The battery should be able to provide a consistent output. It should not fluctuate otherwise one won't be able to run the vehicle at a specific speed and power. As a result, the electrical flow and battery output must be steady. This is quite crucial.
- Energy Density or Specific Energy: The energy density refers to the entire amount of energy that may be stored per unit mass or volume. This defines how long your device will operate before it is required to be recharged. The energy density of a battery is used to determine by the amount of energy that a battery can store and supply per unit volume (Wh/L) or weight (Wh/kg) *(Koniak & Czerepicki, 2017)*, *(Huang et al., 2022)*.
- High Energy Capacity: This means, the energy density must be quite high. The vehicle can run several hundreds of kilometers on a single charge *(Gurjar 2017)*.

- High Energy Efficiency: High energy efficiency means that the power per unit of energy must be very high *(Gurjar, 2017)*.
- Power Density or Specific Power: Power density or specific power means the maximum rate of energy discharge per unit mass or volume. The power density of a battery is measured by the amount of power that the battery is capable to supply per unit of weight (W/kg) *(Battery_University 2017; Huang et al. 2022)*.
- High Peak Output Power: High peak output of power per unit of mass or volume. It needs to be able to operate with variable operating temperatures, whether at low temperatures or at high altitudes *(Gurjar 2017)*.
- Safety: It is essential to ensure that the temperature at which you manufacture the device will operate. Some battery components will break down and may undergo exothermic reactions at high temperatures *(Gurjar, 2017)*.
- Maintenance-free: If the battery needs frequent maintenance, it will discourage the users. Therefore, it should be maintenance-free *(Gurjar 2017)*.
- Cost: It is important that the cost of the battery you choose must be reasonable given its performance and should not significantly raise the project's overall cost *(Huang et al. 2022)*.
- Reliability: At any temperature or in any other situation, reliability will not be lost which means it will provide power at any time or anywhere *(Gurjar 2017)*.
- Battery Life or Cycle Life: Battery life, which is determined by the number of charging cycles that a battery can sustain, is another aspect to consider. The objective is to create batteries that can withstand a higher number of charge and discharge cycles *(Koniak & Czerepicki, 2017)*, *(Huang et al. 2022)*.
- Good Charge Retention: It means it shouldn't discharge very rapidly after being charged. It should maintain its capacity and discharge gradually *(Gurjar 2017)*.
- Fast Charge: The ability to accept quick charging; if it takes too long to recharge, consumers will be frustrated. Therefore, it must be capable of receiving and accepting quick charging *(Gurjar 2017)*.
- Withstand Over-Charge and Over-Discharge: It must also withstand over-charge and over-discharge. After discharge, it should not be completely turned off. Even if it is over-discharged due to an emergency, it should be able to recharge again quickly *(Rivera et al. 2021)*, *(Battery_University 2017)*, *(Gurjar 2017)*.
- Charging Current: It is referred to as the highest current that may be used to charge the battery. In actuality, if the battery safety circuit is built in, a maximum current of 1/2A can be applied, however, 500 mA is the ideal range for a battery charge *(Battery_University, 2017; Huang et al. 2022)*.
- Charging Voltage: The maximum voltage that must be delivered to the battery to successfully charge it is referred to as the charging voltage. In general, 4.2V is thought to be the ideal charging voltage *(Battery_University, 2017; Huang et al. 2022)*.
- Rugged, Robust, and Resistant: It should be rugged, robust, and resistant to any type of difficult situation, such as harsh weather and rough typography *(Gurjar 2017)*.
- Safety: It must be safe to use. And in the event of accidents, it should not explode or make accidents. Therefore, safety is the prime thing in this way *(Gurjar, 2017)*.
- Environmental friendly: It is recommended to use inexpensive and environmentally friendly materials. Therefore, these materials should not be used once discarded, otherwise, it will harm the environment. Therefore, ecologically acceptable materials as well as inexpensive and extremely inexpensive materials can be *(Gurjar 2017; Huang et al. 2022)*.

4. History on Battery Chemistries

The lead-acid battery was invented by French scientist Gaston Plante in the late 19th century. It was the first rechargeable battery used in automobiles *(Parag Jose & Meikandasivam, 2017)*. Various types of batteries were developed in the following century, such as Nickel-based (Ni-based) and Lithium-based (Li-based). The circumstances of the oil crisis and the development of energy storage technologies Lithium-Ion (Li-ion) batteries got more popularities and in the late 20th century, EVs progressively became a significant component of the automobile industry *(Parag Jose & Meikandasivam, 2017)*.

Other types of batteries are further discussed below.

4.1 Conventional Batteries

4.1.1 Lead Acid Battery (PbO_2)

One of the world's oldest battery technologies and one of the most rechargeable batteries is the lead acid battery, which was made in 1860. In general, there are two types of lead acid batteries that are widely used: absorbent glass mat batteries and valve-regulated lead acid batteries. Lead crystal batteries, silver calcium batteries, and more are among the several varieties of hybrid lead acid batteries also available. The main components of lead acid batteries are lead, sulfuric acid, and lead oxide. Lead acid batteries have several advantages, including high voltage per cell, low cost, a long lifespan, outstanding performance at room temperature, and so on. On the other hand, lead acid batteries have a limited lifespan, bulky in size, a high depth of discharge, and low energy density . The performance of lead acid batteries is not satisfactory in comparison to other types of batteries *(Singh, Karandikar, & Kulkarni 2021)*. If its disposal is not managed appropriately then lead toxicity might contaminate soil *(Shen et al. 2019)*. Therefore, lead-acid batteries are no longer appropriate for use as the major onboard energy storage technology in today's EVs. A lead acid battery has a positive plate made of lead peroxide (PbO_2) and a negative plate made of sponge lead (Pb), which are reacted upon by a diluted sulfuric acid (H_2SO_4) electrolytic solution.

Discharging: A lead acid battery's electrolyte splits into H_2 and SO_4 during discharge, producing water (H_2O) and reducing the amount of acid. Sulfate (SO_4) reacts with lead (Pb) plates to create lead sulfate ($PbSO_4$), as illustrated in Figure 1 and Equation (1) *(Instrumentation_Tools, 2018)*.

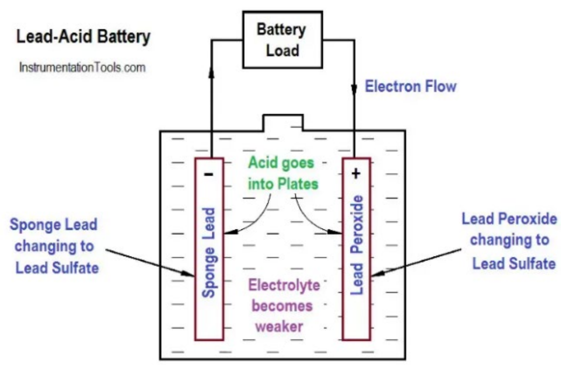

Figure 1. Chemical action of Lead Acid Battery (PbO_2) during discharge *(Instrumentation_Tools, 2018)*.

The discharge; shown in Equation (1) *(Instrumentation_Tools, 2018)*:

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O \quad (1)$$

Charging: The sulfuric acid in the electrolyte (H_2SO_4) reacts with the lead and lead dioxide in the plates to form lead sulfate ($PbSO_4$) is created during the discharge of a lead acid battery. During the recharge process, this reaction is reversed and lead sulfate is pushed back into the electrolyte. This decreases the amount of sulfate on the plates and raises the specific gravity, which restores the battery's capacity, as illustrated in Figure 2 and Equation (2) *(Instrumentation_Tools 2018)*.

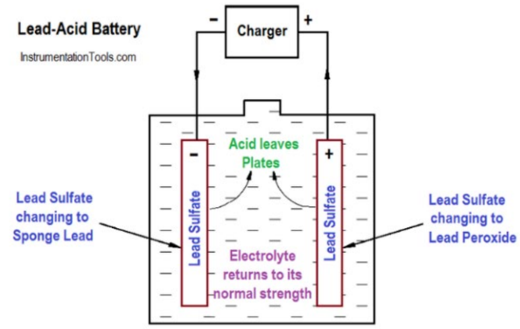

Figure 2. Chemical action of Lead Acid Battery (PbO_2) during charging *(Instrumentation_Tools, 2018)*.

The charge; shown in Equation (2) *(Instrumentation_Tools, 2018)*:

$$PbO_2 + Pb + 2H_2SO_4 \leftarrow 2PbSO_4 + 2H_2O \quad (2)$$

A Lead Acid battery is the traditional type of battery used in most gasoline powered vehicles to start the engine. Beyond that, some electric vehicles of the early 90s, like the GM EV1 or Ford Ranger EV, used lead acid batteries. However, due to their lower efficiency, lead acid batteries are no longer utilized by EV manufacturers. More succinctly, lead acid batteries are susceptible to cold temperatures and not as durable as other EV batteries. Not to mention they are heavy and bulky *(Koohi-Fayegh & Rosen 2020)*.

4.1.2 Nickel-Based Battery

Demand for Nickel-based batteries has increased over the past decades and it has proven to be commercially viable. Rechargeable batteries, which employ aqueous alkaline-based electrolytes such as potassium hydroxide (KOH) and oxyhydroxide cathodes, are all related to nickel-based batteries. Among the different nickel-based chemistries, Nickel-Cadmium (NiCd) and Nickel-Metal Hydride (NiMH) are often used. Nickel Hydroxide is used as the positive electrode in NiCd and NiMH batteries, whereas Cadmium Hydroxide is used as the negative electrode in NiCd cells, and Metal Hydride is used as the negative electrode in NiMH cells. Even though the cost of nickel-based batteries is significantly higher, these batteries have the unique governing qualities of delivering a continuous high capacity power supply, having a long lifespan, and rapid recharging, especially in terms of energy efficiency. Batteries made of nickel-based substances, such as Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Nickel-Iron (NiFe), and Nickel-Zinc (NiZn) batteries. Others are Nickel-Hydrogen (NiH), Manganese-Zinc, Silver-Hydrogen, and Sodium-Nickel Chloride batteries *(J. Wang, Li, & Wei 2022)*,

Nickel is more electrochemically superior and lighter than lead, but the price of Ni-based batteries is up to ten times higher than lead-acid batteries *(Hadjipaschalis, Poullikkas, & Efthimiou 2009)*. In 1899, a Swedish scientist invented the nickel-cadmium (NiCd) battery. It has a lower specific energy density than Nickel Metal Hydride (NiMH) batteries, but EV powertrains prefer its great dependability at low temperatures and inexpensive cost. The European Union has restricted the use of Cd in batteries due to its toxicity. NiMH batteries are ecologically safe when disposed of using common disposal techniques like landfills and have a wide working temperature range and high energy density *(Ovshinsky, Fetcenko, & Ross, 1993)*. Ni-based batteries have limited large-scale commercial uses in the EV sector due to their lower specific energy, faster self-discharge rates, and higher heat production rates at high operating temperatures *(Sujitha & Krithiga, 2017)*.

The Electromechanical charging and discharging procedure for Nickel Cadmium (NiCd) battery has it that the battery has a negative plate anode made of Metallic Cadmium (Cd) and a positive plate cathode made of Nickel Oxide Hydroxide (NiO(OH)). 30% potassium hydroxide (KOH) in distilled water is employed as the electrolyte, as illustrated in Figure 3 *(Engineers_Garage, 2017)*.

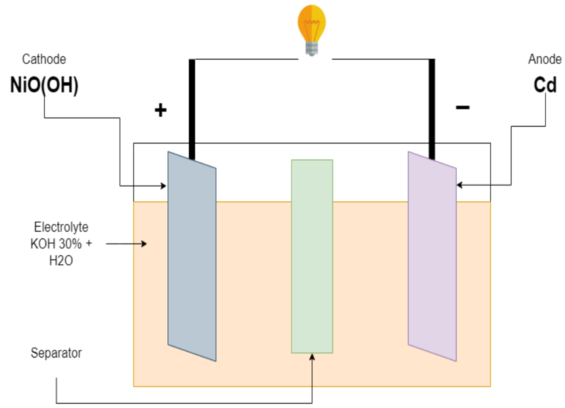

Figure 3. Nickel Cadmium (NiCd) battery *(Engineers_Garage, 2017)*.

When the load is attached to the terminal, the battery begins to discharge as shown in Figure 4. The potassium hydroxide (KOH) electrolyte separates into a positive potassium ion (K^+) and a negative hydroxyl ion (OH^-). The potassium ion (K^+) goes toward the positive electrode (anode) and the hydroxyl ion (OH^-) goes toward the negative electrode (cathode). The negative electrode releases electricity, which is received by the positive electrode via an external connection. This causes current to flow from the positive electrode to the negative electrode through the charge *(Engineers_Garage, 2017)*.

The following Equation (3)-(5) and Figure 4 (Engineers_Garage, 2017) shows the chemical reactions that take place during discharging. At the cathode; the reaction is as follows:

$$Cd + 2OH \rightarrow Cd(OH)_2 + 2e^- \quad (3)$$

At the anode; the reaction is as follows:

$$NiO(OH) + H_2O + 2e^- \rightarrow 2KOH + Ni(OH)_2 + OH \quad (4)$$

The overall reaction is as follows:

$$Cd + 2NiO(OH) + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2 \quad (5)$$

The charging procedure follows that when the hydroxyl ions (OH^-) move toward the anode, while the potassium ions (K^+) move toward the cathode. In order to discharge, the reaction is reversed. $Ni(OH)_2$ is transformed into NiO(OH) by the positive electrode and releases electrons. $Cd(OH)_2$ is transformed into Cd by a negative electron taking an electron from the external connections *(Engineers_Garage, 2017)*.

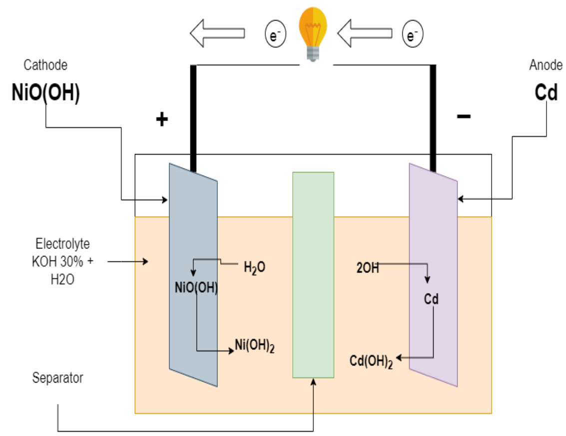

Figure 4. Discharging the NiCd battery *(Engineers_Garage, 2017)*.

The following Equation (6)-(8) and Figure 5 (Engineers_Garage, 2017) shows the chemical reactions that take place during charging. At the cathode; the reaction is as follows:

$$Ni(OH)_2 + OH^- \rightarrow NiO(OH) + H_2O + 2e^- \quad (6)$$

At the anode; the reaction is as follows:

$$Cd(OH)_2 + 2e^- \rightarrow Cd + 2OH \quad (7)$$

The overall reaction is as follows:

$$2Ni(OH)_2 + Cd(OH)_2 \rightarrow Cd + 2NiO(OH) + 2H_2O \quad (8)$$

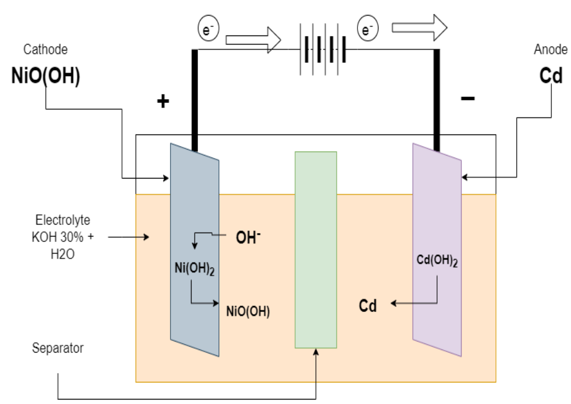

Figure 5. Charging of NiCd battery *(Engineers_Garage, 2017)*.

The electromechanical reaction of Nickel Metal Hydride (NiMH) battery follows that when the anode of the simplified cell is made of Metal Hydride (MH); the cathode is made of Nickel Hydroxide $Ni(OH)_2$. It is a hydrogen-absorbing alloy, the electrolyte is a potassium hydroxide (KOH) aqueous solution, and the separator is built of polyolefin material, as illustrated in Figure 6 *(H. Chen et al. 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*.

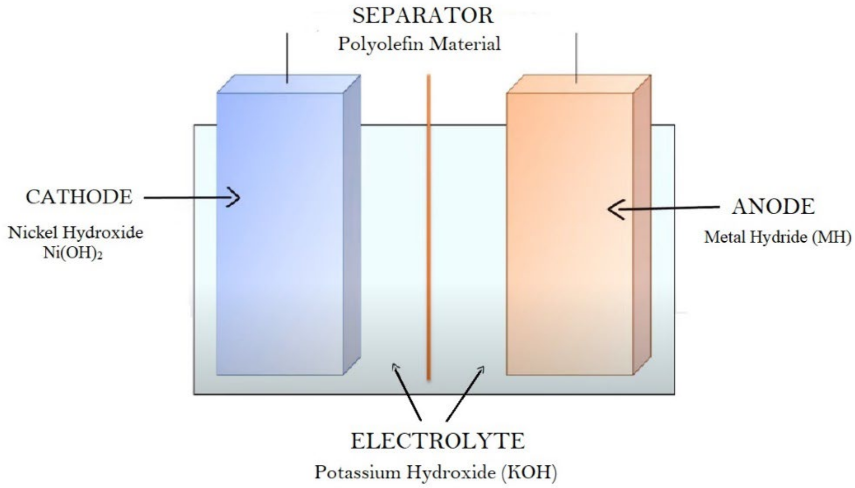

Figure 6. Parameters of Nickel Metal Hydride (NiMH) battery *(H. Chen et al. 2019; Koohi-Fayegh & Rosen 2020; Long et al. 2018)*.

Charging: During battery charging, the cathode cell is Nickel Hydroxide $Ni(OH)_2$ and the anode is Metal (M). When the charger is connected between the electrodes, current (i) flows through the cathode. Potassium Hydroxide (KOH) is the electrolyte; which separates into the positive potassium ion (K^+) and the negative hydroxide ion (OH^-). The Hydroxide ion (OH^-) reacts with Nickel Hydroxide $Ni(OH)_2$ to produce Nickel Oxide Hydroxide NiO(OH) produces water also. Generates electrons that go through the external circuit and reach at the anode. At the anode, water reacts with metal form a metal hydride that produces a hydroxide ion, as illustrated in Figure 7 *(H. Chen et al. 2019; Koohi-Fayegh & Rosen 2020; Long et al. 2018)*.

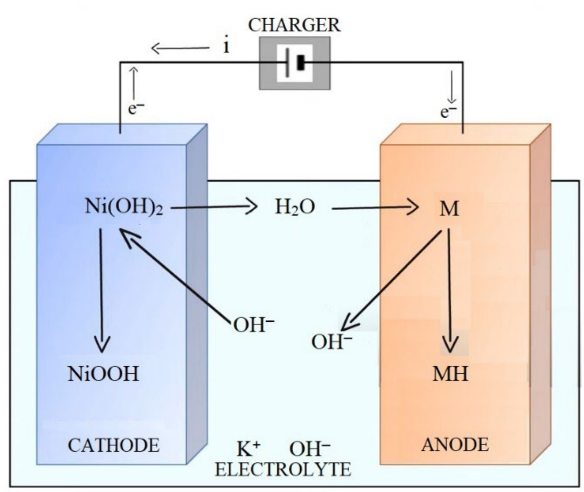

Figure 7. The charging of chemical action of Nickel Metal Hydride (NiMH) battery *(H. Chen et al., 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*.

At the cathode; Nickel Hydroxide $Ni(OH)_2$ reacts with Hydroxide ion (OH^-) to form Nickel Oxyhydroxide (NiOOH) and water as shown in Equation (9) *(H. Chen et al. 2019; Koohi-Fayegh & Rosen, 2020; Long et al.2018)*:

$$Ni(OH)_2 + OH^- \rightarrow NiOOH + C_2O + e^- \quad (9)$$

At the anode; Metal (M) reacts with water (H_2O) to form metal hydride (MH) and hydroxide ions (OH^-) as shown in Equation (10) *(H. Chen et al., 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*:

$$M + H_2O + e^- \rightarrow MH + OH^- \quad (10)$$

All cell reaction; as shown in Equation (11) *(H. Chen et al., 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*:

$$Ni(OH)_2 + M \rightarrow NiOOH + MH \quad (11)$$

Discharge: During the cell discharge at the cathode Nickel Oxyhydroxide NiOOH is generated and at the anode Metal Hydride (MH) is generated during charging. Across the electrodes, a load is connected. The potassium hydroxide (KOH) electro-electrolyte splits into positive potassium ions (K^+) and negative hydroxide ions (OH^-). Then, the Hydroxide ion (OH^-) reacts with Metal Hydride (MH) to form metal (M) giving away water (H_2O) and electrons are produced. These electrons flow through the external circuit and illuminate the load and reach the cathode. At the cathode, water reacts with Nickel Oxyhydroxide (NiOOH) to generate Nickel Hydroxide $Ni(OH)_2$, releasing hydroxide ions. The reactions are reversed during discharging, as illustrated in Figure 8 *(H. Chen et al. 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*.

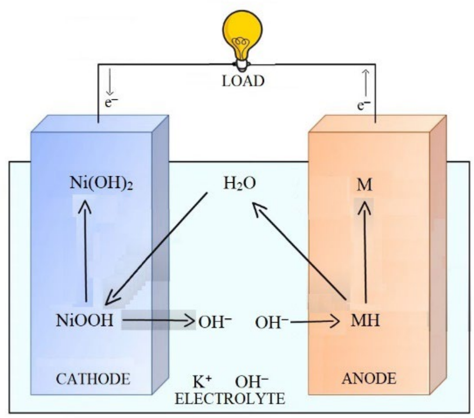

Figure 8. The discharging of chemical action of Nickel Metal Hydride (NiMH) battery *(H. Chen et al., 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*.

At the cathode; Nickel Oxyhydroxide (NiOOH) reacts with water (H_2O) to form Nickel Hydroxide $Ni(OH)_2$ and Hydroxide ion (OH^-) as shown in Equation (12) *(H. Chen et al., 2019; Koohi-Fayegh & Rosen, 2020; Long et al.2018)*:

$$NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^- \quad (12)$$

At the anode; Metal Hydride (MH) reacts with hydroxide (OH^-) to form Metal (M) water (H_2O) to form metal reacts with water (H_2O) to form metal hydride (MH) and hydroxide ion (OH^-) as shown in Equation (13) *(H. Chen et al., 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*:

$$MH + OH^- \rightarrow M + H_2O + e^- \quad (13)$$

All cell reaction; as shown in Equation (14) *(H. Chen et al., 2019; Koohi-Fayegh & Rosen, 2020; Long et al., 2018)*:

$$NiOOH + MH \rightarrow Ni(OH)_2 + M \quad (14)$$

Nickel Metal Hydride batteries are frequently used as an alternative to lead-acid batteries, which were phased out by vehicle manufacturers. Some of the first electric vehicles fitted with nickel metal hydride batteries include the Toyota RAV4 EV, Honda EV Plus, and Ford Ranger EV. But nickel metal hydride batteries have not yet become popular in the electric vehicle industry because they are expensive and ineffective at high temperatures. In addition, nickel metal hydride batteries discharge faster than other types of batteries. For this reason, nickel metal hydride batteries are more commonly seen in hybrids than in electric vehicles. Surprisingly, nickel metal hydride batteries are more durable than lithium-ion or lead-acid batteries *(H. Chen et al. 2019; Koohi-Fayegh & Rosen, 2020; Long et al. 2018)*.

4.2 Contemporary Batteries

A new technology known as the Lithium-Ion (Li-ion) battery was invented in 1991, removing all the drawbacks of battery technology. SONY was the first to use Li-ion rechargeable batteries in commercial electronic products. It has a higher efficiency, longer life cycle, no memory effect, high power and energy density, low self-discharge rate, and high-temperature efficiency. It also has a relatively longer travel distance, which is nearly three times bigger than the range of a lead acid battery. All these characteristics make this technology most suitable for EV applications *(Sun, Li, Wang, & Li, 2019; D. Wang et al. 2021; Xia-yan, Jun-teng, Yao, Qiu-yu, & Yong-chang, 2022)*.

In contemporary EVs, the Li-ion battery has dominated the modern market for energy storage devices for the past two decades (Y. Liu et al. 2019). According to the kind of electrolyte the Li-ion batteries may be divided into three categories those are polymer-based, liquid-based, and all-solid-state. The majority of liquid electrolytes are organic liquids or aqueous electrolytes. They have low costs and high technical maturity. However, due to the liquid qualities, its operational temperature range is limited, especially at very low or very high temperatures (Miao, Hynan, Von Jouanne, & Yokochi 2019).

The polymer-based electrolytes provide more power and greater specific energy *(Chian et al., 2019; Wu, Chen, Danilov, Eichel, & Notten, 2023)*. During high-rate discharging, the heat generation rate of the polymer-based cell significantly increases *(Vidyanandan 2019)*. Although better and lower cost polymer separators have been developed, but their overall production costs remain greater than those of the majority of other Li-ion batteries *(Alessia, Alessandro, Maria, Carlos, & Francesca, 2021)*. A 100 kWh Li-ion polymer battery was successfully installed on a solar-powered EV *(Noudeng, Quan, & Xuan, 2022)*. To achieve better energy density, higher operating temperature, and safety performance, several researchers have suggested using solid biopolymer electrolyte *(Lai et al. 2022)*. It has been examined and demonstrated that the high-energy lithium metal polymer (LMP) battery has a broad operating range up to 80°C *(L. Zhou et al. 2023)*. Commercial LMP battery use in HEVs for port operations with a wide temperature range of –20ºC to 65ºC occurred in 2018 *(Zeng et al. 2019)*. If the polymer cell is considered as a quasi-solid-state battery, the upcoming ASSB has the potential to be the next generation EV battery due to its high energy density and great safety performance. Since it is still being developed for commercial use. It is described as a potential battery in the section that follows.

The positive electrode (cathode) is built of a composite material called lithium-cobalt oxide, whereas the negative electrode (anode) is formed of graphite. As electrolytes, lithium salts in organic solvents are employed. To separate the electrodes, a separator is employed, as illustrated in Figure 9 *(Engineers_Garage, 2017)*.

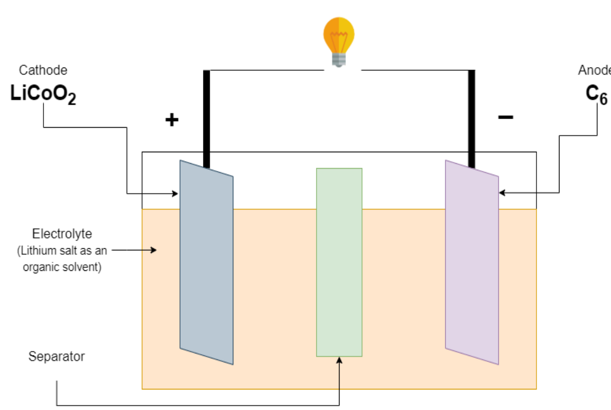

Figure 9. Parameter of Li-ion battery *(Engineers_Garage, 2017)*.

Discharging: The load is attached to the battery terminal when the battery discharge. The negative electrode releases Lithium-Ion, and which moves towards the electrolyte. A positive electrode absorbs the Lithium-Ion. Electrons are also released from the negative electrode and travel along the external wire to the positive electrode. This supplies us an electric current to our circuit, as illustrated in Figure 10 *(Engineers_Garage 2017)*.

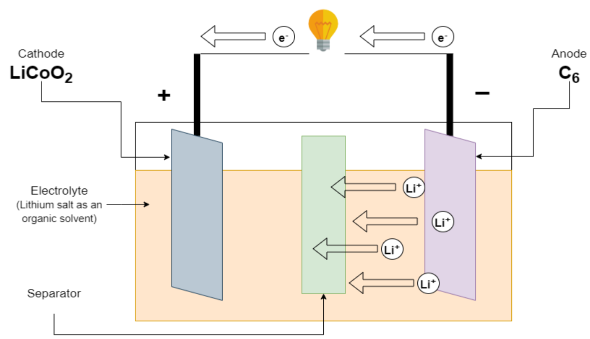

Figure 10. Chemical discharge of Li-ion battery *(Engineers_Garage, 2017).*

The following Equation (15)-(17) (Engineers_Garage, 2017) shows the chemical reactions that take place during discharging. At the anode; the reaction is as follows:

$$LiC_6 \rightarrow C_6 + Li^+ + e^- \quad (15)$$

At the cathode; the reaction is as follows:

$$CoO_2 + Li + e^- \rightarrow LiCoO_2 \quad (16)$$

The overall reaction is as follows:

$$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2 \quad (17)$$

Charging: When the battery charges, it is attached to the charger. A negatively charged electron is lost by the positive electrode. To maintain the charge balance at the negative electrode, an equal amount of positively charged ions are dissolved in the electrolyte solution. When the lithium-ion reaches the positive electrode, it is absorbed by the graphite. In addition to depositing electrons into the graphite anode to "tie" up the lithium ion, this absorption process also deposits electrons, as illustrated in Figure 11 *(Engineers_Garage, 2017)*.

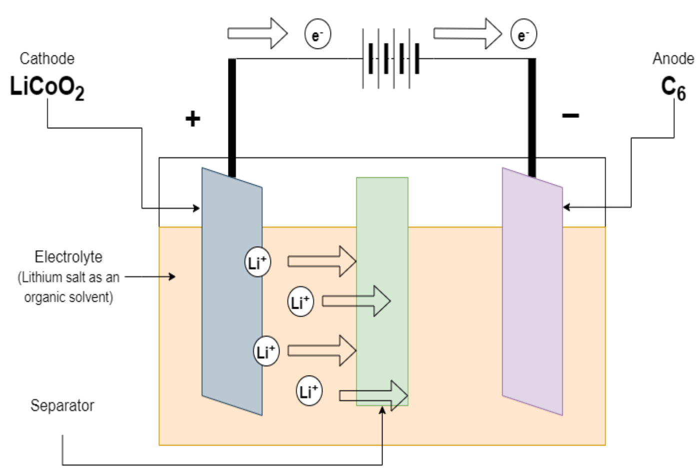

Figure 11. Chemical charge of Li-ion battery *(Engineers_Garage, 2017)*.

The following Equation (18)-(20) (Engineers_Garage, 2017) shows the chemical reactions that take place during charging.

At the cathode; the reaction is as follows:

$$LiCoO_2 \rightarrow CoO_2 + Li + e^- \quad (18)$$

At the anode; the reaction is as follows:

$$C_6 + Li^+ + e^- \rightarrow LiC_6 \quad (19)$$

The overall reaction is as follows:

$$C_6 + LiCoO_2 \rightarrow LiC_6 + CoO_2 \quad (20)$$

Lithium-Ion batteries are used in the majority of electric cars today. This is because they are lighter and more energy efficient than lead acid or nickel metal hydride batteries. They are also less likely to overheat at high temperatures, which helps to minimize the possibility of a fire breaking out. In addition, compared to different batteries types, lithium-ion takes longer to discharge. Some electric vehicles have a longer range with lithium-ion batteries that can travel more than 800 km on a full charge. It's even more impressive that a Tesla with a lithium-ion battery comes with an eight-year warranty, but the expected lifespan of a Tesla is between 300k, miles to 500k, miles. However, not all lithium-ion batteries are the same. The majority of high end electric vehicles come with lithium-ion batteries that include a positive cobalt electrode. On the other hand, some EV manufacturers are switching to lithium iron phosphate batteries for entry level electric vehicles *(Koohi-Fayegh & Rosen 2020)*.

Despite its advantages, one of the main disadvantages of Li-ion batteries is that they are not environmentally friendly when disposed of. Not to mention mining for Li-ion raw materials can disrupt ecosystems that are important to wildlife and indigenous communities. The good news is that there are promising alternatives to more environmentally friendly Li-ion batteries. In addition, Li-ion batteries can be recycled after disposal *(Koohi-Fayegh & Rosen, 2020)*.

4.3 Future Battery

Future batteries are cutting-edge battery technologies that are presently being developed and might eventually lead to the next generation of widely used, commercial batteries for EVs. Examples of these technologies include Lithium-Ion Air (LiO_2) batteries, Lithium-Ion Silicon (LiSi), Lithium-Sulfur (LiS), All-Solid-State Battery (ASSB), Sodium-ion (Na-ion) Battery, Zinc-ion (Zn-ion), and others *(Senthil, Park, Shaji, Sim, & Lee 2022)*. None-aqueous electrolytes are flammable, unstable at high temperatures and toxic. Aqueous electrolytes are nonflammable and have better safety performance *(Senthil et al., 2022)*. The aqueous-based Li-ion battery has found employment in airplanes and submarines because to its superior safety performance and dependability, which has also drawn the attention of EV developers to create commercial applications *(Ryu, Song, Lee, Choi, & Park 2020)*.

The aqueous Li-ion battery with a lithium sulfate (Li_2SO_4) electrolyte has a capacity, energy density, and cycle life of 100Ah/kg, 30Wh/kg, and 1000 cycles, respectively *(Gu et al., 2019; Song et al. 2020)*. A Li-Ion Air (LiO_2) battery has a theoretical specific energy of up to two to three kWh/kg, which is higher than the low specific energy of an aqueous-based battery *(Chen et al. 2021)*.

Due to its higher energy density, broader operating temperature window, improved safety performance, and cheaper production costs as a result of the abundance of S mass in the earth's crust, Li-S batteries have a promising future. The most significant technological challenge is the passivation of the lithium anode as a result of its reactivity with insoluble Li-S particles, which results in a high rate of self-discharge and rapid capacity deterioration *(Meng et al. 2021; Peters, Baumann, Zimmermann, Braun, & Weil, 2017)*.

Theoretically, the anode capacity of a Li-Si battery is around 4,200 Ah/kg, which is about 10 times more than some graphite anodes used in commercial Li-ion batteries *(Luo et al., 2017)*. Although the production of high-performance nanostructured silicon materials is costly and unstable, advances in technology coating nanotechnology and manufacturing process engineering have led to the development of commercially viable large-scale products *(P. Li et al., 2018)*. By using the pyrolysis technique, a second layer of carbon was added to the surface of the silicon nanoparticles enclosed in the electros pun carbon nanofibers. In comparison to the material without a second carbon coating, the novel silicon based anode material has a greater specific capacity of 936.1 Ah/kg in the first discharge cycle and 753.5 Ah/kg in the 100th discharge cycle *(S. Liu et al. 2019)*.

Due to its outstanding energy density and safety features, Li-Ion ASSB is now a hot issue and a possible game changer in the EV market. Li-ion ASSBs have emerged as an intriguing alternative to traditional lithium-ion batteries for energy storage *(Shi et al., 2020)*. The most promising next generation battery technology is lithium-ion ASSBs. The electrolyte is the primary distinction between Li-ion and Solid State batteries. Solid state batteries employ solid electrodes composed of glass, ceramic, or non-flammable lithium phosphate, whereas Li-ion batteries use flammable liquid electrolyte solutions *(Z. Deng, Hu, Lin, Kim, & Li, 2021)*.

A company by the name of Fisker patented for unveiled an SSB in 2017 with an energy density of more than 400Wh/kg and no liquid electrolyte. This battery is safe to use since it has inorganic solid electrolytes that are none flammable at rising temperatures. Additionally, because self-discharge is decreased, high capacity, high voltage materials may be employed to make batteries that are denser, lighter, and have higher safety performance *(Z. Deng et al. 2021)*. The sulfur cathode's poor conductivity and rapid expansion are its principal barriers to future adoption *(T. Yang et al., 2019)*. To obtain an energy density of more than 1400Wh/kg with sustained cycle performance at room temperature, intrinsically change the reaction pathway of sulfur-based cathodes with specific redox activities. It is also one of the largest energy storage systems in the world *(Y.-G. Lee et al.2020; Sanpei Zhang et al. 2020)*.

The potential to replace cheaper and safer Li-ion, Na-ion, and Zn-ion batteries are recently becoming the most popular for EVs industry, because of the high abundance, low manufacturing costs, raw materials in the earth's crust, great safety, and respect for the environment *(J. Deng, Luo, Chou, Liu, & Dou, 2018; Ming, Guo, Xia, Wang, & Alshareef, 2019; Placek 2022)*.

Create a Zn-ion aqueous chemical self-charging battery with a CaV6O16.3H2O cathode that can discharge at 239 Ah/kg and display an open circuit voltage (OCV) of 1.05 V *(SS Zhang, Xu, & Jow, 2002)*. To achieve a specific energy of 214Wh/kg and a stability of 300 cycles, a novel aqueous based Zn-ion battery with a porous crystal cathode and zinc pyrovanadate (Zn3(OH)2V2O72H2O) nanowires was developed *(Yamauchi et al. 2020)*. At the same time, a battery with an aqueous based Zn(CF3SO3)2 electrolyte and an H2V3O8 nanowire cathode and zinc anode has a specific energy of 432.8 Ah/kg and a stability of more than 1,000 cycles Period *(H. Chen et al. 2020)*.

Na ceramic superionic conductive electrolyte (NASICON) and a Na metal anode make up a Na-ion ASSB (Ates, Keller, Kulisch, Adermann, & Passerini, 2019). The electrolyte wetting treatment and the novel polymer/NASICON/polymer sandwich structure efficiently lowered the resistance on the Na/ceramic contact and avoided dendritic formation. Na-ion batteries will play an important role as lithium prices continue to rise and safer Na-ion electrolytes become available in the future (J. Li & Passerini 2021).

When a LiO2 battery is discharged, Li metal is oxidized to Li^+ at the anode and O_2 is reduced at the cathode, creating solid Li_2O_2. During charging, the reverse cathode reaction decomposes Li_2O_2 and releases O_2 and Li^+. The Li metal is deposited on the anode by reverse reaction with the anode *(H. C. Lee et al., 2019; F. Wang & Li, 2018)*.
The electromechanical process for charging and discharging Lithium-Ion Air (LiO_2) batteries is shown in Figure 12 and Equations (21)-(23) *(H. C. Lee et al. 2019; F. Wang & Li 2018)*.

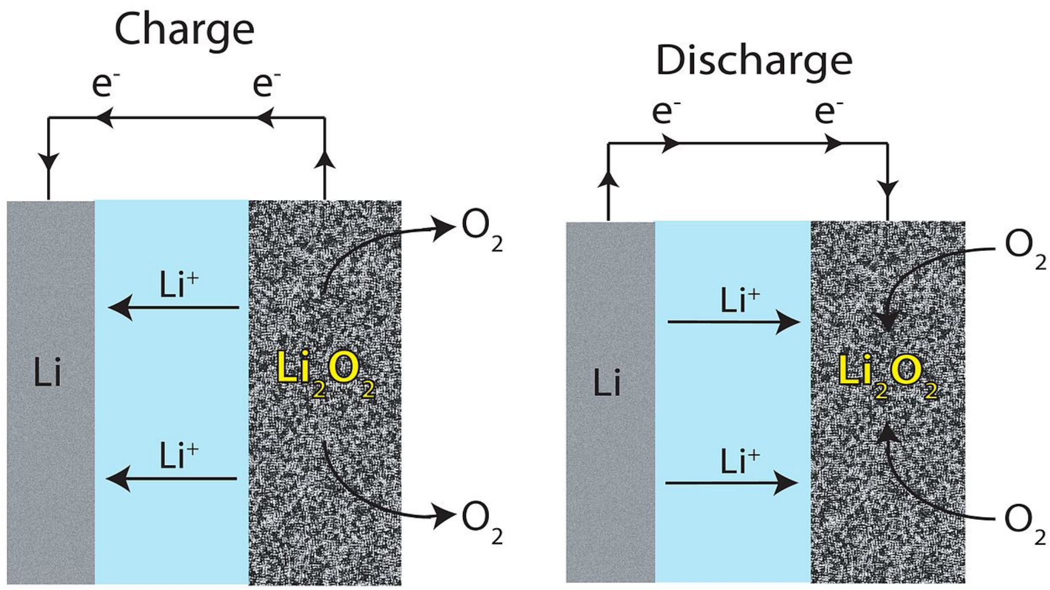

Figure 12. Charging and discharging cycle diagram of a Lithium-Ion Air battery *(H. C. Lee et al., 2019; F. Wang & Li, 2018)*.

At the anode; the reaction is as follows:

$$2Li \leftrightarrow 2Li^{+} + 2e^{-} \quad (21)$$

At the cathode; the reaction is as follows:

$$2Li^{+} + 2e^{-} + O_2 \leftrightarrow Li_2O_2 \quad (22)$$

The overall reaction is as follows:

$$2Li + O_2Li \leftrightarrow Li_2O_2 \quad (23)$$

Solid sulfur from the cathode dissolves in the electrolyte during discharge, creating S_8. The liquid S_8 is then electrochemically reduced at the cathode to create intermediate products known as lithium polysulfide species (Li_2Sx), followed by anode oxidation of Li metal to Li+ ions. In the liquid electrolyte, the polysulfide species (Li_2Sx $2 < x \leq 8$) dissolve and diffuse from the cathode to the electrolyte/separator side. The length of the polysulfide chain is reduced during discharge, which has an impact on the viscosity, mobility, and solubility of Li_2Sx compounds. S_8 is totally reduced to S^{2-} (Li_2S) by the conclusion of the discharge, and the anode is completely free of Li metal. Figure 13 depicts this procedure schematically. During charging, reversal processes take place, with Li+ ions depositing as Li metal at the anode and lower order polysulfides oxidizing from S^{2-} to SLi_8^{2-} and finally S_8(s) *(Wen et al. 2020)*.

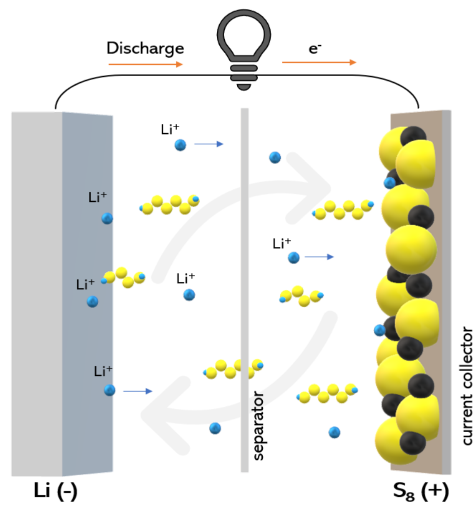

Figure 13. Chemical discharge of LiS battery *(Wen et al.2020)*.

At the cathode; the reaction is as follows:

$$S_8 + 16Li^+ + 16e^- \leftrightarrow 8Li_2S \quad (24)$$

At the anode; the reaction is as follows:

$$Li \leftrightarrow Li^+ + e^- \quad (25)$$

At the discharge; the reaction is as follows:

$$S_8 + 16Li \rightarrow 8Li_2S \quad (26)$$

At the charge; the reaction is as follows:

$$8Li_2S \rightarrow S_8 + 16Li \quad (27)$$

Lithium Sulfur battery is another alternative to lithium-ion batteries. Similar to solid-state batteries, Lithium-sulfur batteries can provide longer runtimes than lithium-ion batteries. According to the European Commission, they are also cheaper to produce and have less impact on the environment than lithium-ion cobalt batteries. Lithium-sulfur batteries are not seen in EVs because they have a short lifespan. However, researchers are working on experiments that might solve this problem *(Koohi-Fayegh & Rosen 2020)*.

Solid State Battery: Solid state batteries are currently under development and are not yet used in electric vehicles. The first solid state battery powered electric vehicles might be on the road around by 2025, according to Toyota. Compared to lithium-ion batteries, solid-state batteries consume more energy. Solid-state batteries also have another benefit that is they don't take up too much space compared to lithium-ion batteries. Due to the weight advantage, solid-state batteries can double the range of electric vehicles and improve performance. However, solid-state batteries are still in the research stage until they are mass-produced, one won't know if they are better than lithium-ion batteries *(Koohi-Fayegh & Rosen 2020)*.

4.3.1 Classification of Lithium-ion batteries.

Lithium-ion batteries can be classified into the following categories:

Lithium Cobalt Oxide (LCO)

High specific energy is provided by lithium cobalt oxide ($LiCoO_2$) batteries, which are often used in mobile phones, laptops, notebooks and other devices with low discharge rates. These cells have a high specific energy range of

175Wh/kg to 240Wh/kg and are characterized by great electrical efficiency, however they have a very low thermal stability. It is reasonably priced and of average performance. It is unsuitable for EVs because of its low specific capacity, brief lifespan, and low level of safety *(Yuan et al., 2011)*, *(Huang et al., 2022)*, *(Chikkannanavar, Bernardi, & Liu, 2014; W. Li, Erickson, & Manthiram, 2020; X.-G. Yang, Liu, & Wang, 2021)*.

Lithium Nickel Manganese Cobalt Oxide (NMC)

Lithium Nickel Manganese Cobalt Oxide Li(Ni, Mn, Co)O_2 batteries have the benefit of modulating properties for usage as power or energy cells. When used as energy cells, these compounds have the same energy density as lithium cobalt oxide. When used as a power cell, the specific energy is reduced to values ranging from 100Wh/kg to 150Wh/kg, while the specific power capacity is maximized at temperatures above 300°C. These batteries are utilized in the automobile industry, depending on the arrangement, in portable devices. The NMC battery has two key benefits over conventional batteries, namely high specific energy, which encourages its usage in electric bicycles, electric vehicles, and electric powertrains. Secondly, it is inexpensive. Compared to other lithium-ion batteries, it delivers a moderate level of specific power, lifespan, safety, and performance. It has the ability to be converted into either a high specific energy or a high specific power *(Yuan et al. 2011)*, *(Huang et al., 2022)*, *(Chikkannanavar et al. 2014; W. Li et al., 2020; X.-G. Yang et al. 2021)*.

Lithium Manganese Oxide (LMO)

Lithium manganese oxide ($LiMn_2O_4$) batteries are constructed using less costly positive electrodes, due to the lack of cobalt. These battery cells are thought to be utilized as energy cells and as a result, they have low specific energies, ranging from 100 to 150 Wh/kg. In comparison to lithium cobalt oxide, this chemical is generally safer. However, the variance persists at greater temperatures. Comparing LMO to other Li-ion batteries, they offer moderate specific energy, moderate specific capacity, and a moderate level of safety. It has poor efficiency and short lifespan but it is a cheap battery, that's why it is frequently employed in power tools and medical equipment *(Yuan et al. 2011)*, *(Huang et al. 2022)*, *(Chikkannanavar et al. 2014; W. Li et al. 2020; X.-G. Yang et al. 2021)*.

Lithium Iron Phosphate (LFP)

Lithium iron phosphate ($LiFePO_4$) cell chemistry is being studied for improved electrical performance with reduced internal resistance. These batteries have several advantages such as extended life, high rated current, safety, and outstanding thermal stability. However, compared to the lowest Li-ion batteries, these batteries have lower cell voltage and specific energy. Compare to other lithium-ion batteries, the LFP battery has low specific energy this is one of the biggest drawbacks. In addition, it has a medium to high grade in all other categories. Excellent specific capacity, long lifespan, excellent safety, low cost, and moderate performance. It is utilized in electric bikes and other applications that need for a high degree of safety and a lengthy lifespan. If a way to improve the specific energy of the LFP is discovered, it will find an ideal application in EVs *(Yuan et al. 2011)*, *(Huang et al. 2022)*, *(Chikkannanavar et al., 2014; W. Li et al. 2020; Yong Li, Song, & Yang, 2014; X.-G. Yang et al. 2021)*.

Lithium Nickel Cobalt Aluminum Oxide (NCA)

The greatest specific capacity of Lithium Nickel Cobalt Aluminum Oxide Li(Ni, Co, Al)O_2 batteries is compared to various chemistries on the market. Lithium nickel cobalt aluminum oxide batteries are comparable to lithium nickel manganese cobalt oxide batteries in that they offer a high specific energy, a high specific capacity, and a long service life. Low safety and high cost are the drawbacks of this battery type. Power trains are the ideal environment for it to operate *(Yuan et al. 2011)*, *(Huang et al. 2022)*, *(Chikkannanavar et al. 2014; W. Li et al. 2020; Yong Li et al. 2014; X.-G. Yang et al. 2021)*.

Lithium Ion Polymer (LPO)

A lithium-ion polymer battery is a rechargeable battery of lithium-ion technology that employs polymer electrolytes rather than liquid electrolytes. This electrolyte is made out of semi solid (gel) polymers with excellent electrical conductivity. When compared to conventional lithium batteries, these batteries have an exceptionally high energy density (400Wh L1) and are employed in devices like computers where weight is a key factor. Radio controlled aircraft, portable gadgets, mobile devices, and specific electrical equipment. They also have a low self-discharge rate of about 5% per month, thus it can be relatively safe *(Chacko & Chung, 2012; R. Zhang et al.2018)*.

Lithium Titanate Oxide (LTO)

Lithium Titanate Oxide ($Li_4Ti_5O_{12}$) Battery provides excellent safety, a long service life, and high performance, but its specific energy is lower than that of other lithium-ion batteries; nevertheless, it makes up for this with a moderate specific capacity. Additionally, its expensive cost prevents it from being used for commercial applications. This battery has a very rapid recharge time and is ideal for solar energy storage and smart grid generation *(Yuan et al., 2011)*, *(Huang et al. 2022)*, *(Chikkannanavar et al. 2014; W. Li et al. 2020; Yong Li et al. 2014; X.-G. Yang et al. 2021)*.

4.4 Other Types of Batteries:

4.4.1 Silver Batteries

Silver batteries are mostly made up of silver-zinc and silver-cadmium batteries. The fact that a metal cadmium anode and a silver oxide cathode are dissolved in an aqueous potassium hydroxide electrolyte gives zinc-cadmium oxide batteries, also known as silver cadmium rechargeable batteries, its other name. Silver-zinc batteries are made similarly to silver-cadmium batteries, with the exception that metallic zinc is used as the anode instead of metal cadmium. The qualities of low discharge rate and high capacity are found in silver batteries *(Bullock, 2010; Yanguang Li & Dai, 2014; Zamarayeva et al. 2016)*.

4.4.2 Sodium Sulfur (NaS) Battery

One of the current battery technologies with potential use in high energy storage applications is the relative sodium sulfur battery. In these batteries, metal sodium (Na) is used as the anode while sulfur (S) is used as the cathode, and the beta Al_2O_3 ceramic acts as both an electrolyte and an immediate separator instantly. NaS has a high energy density, electricity with a high volume and discharge efficiency (89-92%), and a long life cycle, these materials have a very low price. This type of battery, in particular, has a high-temperature demand of about 350°C and does not self-discharge, an energy density of about 151kW/m3, and a very high efficiency of about 85%, respectively. This type of battery is used in the Ford Ecostar, which was released in 1992-1993 *(Andriollo et al. 2016; Hoque, Hannan, Mohamed, & Ayob, 2017; Smeacetto et al. 2017)*.

4.4.3 Zinc Bromine Battery ($ZnBr_2$)

The zinc bromine battery is a rechargeable battery that produces an electric current, uses a reaction between zinc metal and bromine, with an electrolyte made of an aqueous solution of zinc bromide. A zinc bromine solution is used in zinc bromine batteries, which are stored in two tanks. Bromide is converted into bromine at the positive electrode. It is being developed as a substitute for lithium-ion batteries for stationary power applications, including grid scale and household uses *(Swan, Dickinson, Arikara, & Tomazic, 1994; Y. Zhou 2013)*.

4.4.5 Sodium Nickel Chloride ($Na/NiCl_2$)

Sodium nickel chloride (SNC) batteries, also known as ZEBRA (zero emission battery research activity) batteries. And there are several similarities between sodium sulfur batteries and sodium nickel chloride (SNC) batteries. It is made of sodium and nickel chloride composition. At the optimal working temperature of 270-350°C, solid ceramic functions as both an electrolyte and a separator. The SNC has a specific energy of 125Wh/kg and an energy efficiency of 92%, which is higher than NCd, Pb-acid, and nickel metal hydride (NMH) battery technologies *(Marcondes, Scherer, Salgado, & de Freitas, 2019)*. The main problem of SNC is its long-term storage. SNC batteries have poor energy capacity because of their rapid self-discharge and high internal resistance *(Budde-Meiwes et al. 2013)*. These types of batteries are suitable for usage in electric vehicles *(Sessa, Crugnola, Todeschini, Zin, & Benato 2016)*.

5. Comparison of Different Battery Technologies

Batteries' performances are often based on different characteristics. Therefore, Tables 1 present the technical features of different types of batteries based on Density of power, Density of energy, cost, safety, and lifespan. Another comparison of batteries is also shown in Table 2 which discussed the comparisons of different types of batteries based on nominal voltage, self-discharge, overcharge tolerance, environmental toxicity, memory effects, and technological maturity.

Tables 1 and 2 provide a basic comparison of the technical characteristics of different types of batteries. In terms of power density, energy density, nominal voltage, safety, lifetime, and technological maturity. Lithium-ion batteries are superior, and it is the most popular energy storage device on the electric vehicles market today. A battery has three substances: cathodes, anodes, and electrolytes, which are listed in Table 3 along with the names of the batteries.

Table 1. Batteries characteristics based on density of power and energy, and cost.

Category	Density of power	Density of energy	Cost	Safety	Lifecycle	State of technology adoption	References
Lead Acid	Low	Low	Low	Low	Low	Past	*(Kebede et al., 2021), (Berndt, 1993)*
Lead Crystal	Medium	Medium	Medium	High	High	Past	*(Hu, Li, Ali, & Shen, 2021), (Bukhari, Maqsood, Baig, Ashraf, & Khan, 2015)*
NiCd	Low	Low	Medium	High	High	Past	*(Hadjipaschalis et al., 2009), (Zelinsky, Koch, & Young, 2017)*
NiMH	Medium	Medium	Medium	High	Medium	Past	*(Sujitha & Krithiga, 2017), (Ouyang, Huang, Wang, Liu, & Zhu, 2017)*
Li-ion	High	High	High	High	High	Present	*(Sun et al., 2019), (Liu, Zhang, Wang, & Wang, 2021)*
Li-Air	Very High	Very High	Medium	Medium	Low	Future	*(F. Wang & Li, 2018), (Xu, Wu, Hu, Xie, & Zhang, 2019)*
Li-S	Very High	Very High	Medium	Medium	Low	Future	*(Wen et al., 2020), (Fu, Ma, Zhao, Li, & Su, 2021)*
LiSi	Very High	Very High	Medium	Medium	Low	Future	*(Luo et al., 2017), (T. Zhao, Zhu, Li, Li, & Zhang, 2019)*
ASSB	High	High	Medium	Medium	Medium	Future	*(Senthil et al., 2022), (Baade & Wood, 2021)*
LCO	Low	High	Low	Low	Low	Present	*(Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
LMO	Medium	Medium	Low	Medium	Low	Present	*(Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
NMC	Medium	High	Low	Medium	Medium	Present	*(Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
LFP	High	Low	Medium	High	High	Present	*(Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
NCA	Medium	Medium	Medium	Low	Medium	Present	*(Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
LTO	Medium	Low	High	High	High	Present	*(Chikkannanavar et al., 2014; W. Li et al., 2020; Yong Li et al., 2014; X.-G. Yang et al., 2021)*
LPO	High	High	Medium	Low	Low	Present	*(Chacko & Chung, 2012; R. Zhang et al., 2018)*
Na-S	Medium	High	High	Medium	Medium	Future	*(Hoque et al., 2017), (Conte, 2006)*
Silver Battery	Medium	Low	Medium	Low	Medium	Future	*(Bullock, 2010; Yanguang Li & Dai, 2014; Zamarayeva et al., 2016)*
$NaNiCl_2$/ ZEBRA	High	Low	Low	Medium	High	Future	*(Budde-Meiwes et al., 2013; Marcondes et al., 2019; Sessa et al., 2016)*
$Zn\text{-}Br_2$	Low	High	Low	Medium	Medium	Future	*(Swan et al., 1994; Y. Zhou, 2013)*

Table 2. Batteries characteristics based on voltage rating, discharge rate and overcharge tolerance.

Category	Nominal voltage	Self-discharge	Overcharge tolerance	Environmental toxicity	Memory effects	Technological maturity	References
Lead Acid	Medium	Medium	High	High	Very Low	High	*(Hu et al., 2021; Kebede et al., 2021; Singh et al., 2021; J. Wang et al., 2022), (Berndt, 1993)*
Lead Crystal	High	Medium	High	Low	Very Low	Medium	*(Hu et al., 2021; Kebede et al., 2021; Singh et al., 2021; J. Wang et al., 2022), (Bukhari et al., 2015)*
NiCd	Low	Very High	Medium	High	High	High	*(Boddula, Pothu, & Asiri, 2020; H. Chen et al., 2019; Hadjipaschalis et al., 2009; Long et al., 2018), (Zelinsky et al., 2017)*
NiMH	Low	High	Medium	Low	High	Medium	*(Ovshinsky et al., 1993; Sujitha & Krithiga, 2017), (Ouyang et al., 2017)*
Li-ion	High	Very Low	Low	Medium	Very Low	High	*(Y. Liu et al., 2019; Sun et al., 2019; D. Wang et al., 2021; Xia-yan et al., 2022), (Liu et al., 2021)*

Li-Air	Low	Low	Low	Low	Low	Low	*(H. C. Lee et al., 2019; F. Wang & Li, 2018), (Xu et al., 2019)*
Li-S	Medium	Medium	Low	Low	Low	Low	*(Wen et al., 2020), (Fu et al., 2021)*
LiSi	Low	Low	Medium	Low	Medium	Low	*(P. Li et al., 2018; Luo et al., 2017), (T. Zhao et al., 2019)*
ASSB	High	Low	High	Low	Low	Medium	*(Senthil et al., 2022), (Baade & Wood, 2021)*
LCO	Medium	Medium	Medium	Medium	Medium	Low	*(Huang et al., 2022), (Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
LMO	Low	Low	Medium	Low	Medium	Medium	*(Huang et al., 2022), (Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
NMC	Medium	Medium	High	Medium	Medium	High	*(Huang et al., 2022), (Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
LFP	Low	Low	Medium	Medium	High	High	*(Huang et al., 2022), (Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
NCA	Medium	Medium	Low	Medium	Low	Medium	*(Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021)*
LTO	Low	Medium	Low	High	Medium	Medium	*(Huang et al., 2022), (Chikkannanavar et al., 2014; W. Li et al., 2020; Yong Li et al., 2014; X.-G. Yang et al., 2021)*
LPO	Low	Medium	Low	High	Medium	Low	*(Chacko & Chung, 2012; R. Zhang et al., 2018)*
Na-S	Medium	Low	Medium	Low	Medium	Low	*(Andriollo et al., 2016; Hoque et al., 2017; Smeacetto et al., 2017), (Conte, 2006)*
Silver Battery	Medium	Low	Medium	Low	Medium	Low	*(Bullock, 2010; Yanguang Li & Dai, 2014; Zamarayeva et al., 2016)*
$NaNiCl_2$/ ZEBRA	Medium	High	Medium	High	Medium	Low	*(Budde-Meiwes et al., 2013; Marcondes et al., 2019; Sessa et al., 2016)*
Zn-Br_2	Medium	High	High	Medium	Low	Medium	*(Swan et al., 1994; Y. Zhou, 2013)*

Table 3. Batteries characteristics based on the cathodes, anodes, and electrolytes materials**.**

Battery	Cathode (+)	Anode (-)	Electrolyte	References
Lead Acid	Lead peroxide (PbO2)	Sponge lead (Pb)	Sulfuric acid (H2SO4)	*(Bukhari et al., 2015), (Conte, 2006)*
Lead Crystal	Lead Dioxide (PbO2)	Sponge lead (Pb)	Composite SiO2 electrolyte	*(Singh et al., 2021), (Bukhari et al., 2015)*
NiCd	NiOOH and Ni(OH)2	Cadmium (Cd)	Potassium hydroxide (KOH)	*(Zelinsky et al., 2017), (Karkera, Reddy, & Fichtner, 2021)*
NiMH	Nickel oxyhydroxide (NiOOH)	Hydrogen ions or protons (MH)	Alkaline electrolyte (usually KOH)	*(Ouyang et al., 2017), (Qiao et al., 2019)*
LiO_2	Li metal chip	Ru/B4C	1M LiTFSI in tetraglyme	*(H. C. Lee et al., 2019), (Xu et al., 2019)*
Li-S	Li	S	Lithium trifluoromethanesulfonate (or lithium triflate) LiSO3CF3, Lithium bis (trifluoromethanesulfony)amide (or LiTFSA) LiN(SO2CF3)2	*(Koohi-Fayegh & Rosen, 2020), (Wen et al., 2020), (Fu et al., 2021)*
LiSi	Si nanowires (SiNW)	Li	1 M solution of LiPF6 diluted in a mixture of ethylene (EC), dimethyl carbonate (DMC) and diethyl carbonate (DEC) with a 1:1:1 vol rat	*(P. Li et al., 2018; Luo et al., 2017), (T. Zhao et al., 2019)*
Zn-ion	Zinc	H2V3O8 nanowire	Zn (CF3SO3)2 aqueous electrolyte	*(H. Chen et al., 2020; Yamauchi et al., 2020; SS Zhang et al., 2002)*

Na-S	Na or low potential alloys	Synthesized Na2S-Na3PS4-CMK-3 composite	Solid-state Na11017	*(Hoque et al., 2017)*, *(Conte, 2006)*

The performance is based on the chemical composition of different batteries based on the chemistry, electrolyte, cathode or anode, etc.

Global Top 10 EV Battery Manufacturers in 2023: Even though batteries are the heart and soul of electric vehicles, just a few countries' manufacturers are leading the way in delivering them to the electrification market. The top 10 producers are all Asian companies. Currently, Chinese companies make up 56% of the EV battery market, followed by Korean companies 26% and Japanese manufacturers 10% *(Visual_Capitalist, 2022)*.
There are a number of manufacturers around the world who supply the batteries used in EVs. Table 4 presents a list of the top ten EV battery manufacturers companies, current EV manufacturers, and the types of battery in 2023 *(Cars_Guide, 2022; IEEE_Spectrum, 2022)*.

Table 4. List of EV Battery Manufacturers Company, current EV manufacturers, and the type of batteries being used *(Cars_Guide, 2022; IEEE_Spectrum, 2022; Visual_Capitalist, 2022)*.

Ranked No	EV Battery Manufacturers	Type of Battery	2022 Market Share	Country	EV battery consumer
#1	Contemporary Amperex Technology Co., Ltd. (CATL)	Lithium-ion	34%	China	Tesla, BMW, Honda, Hyundai, Toyota, Peugeot,, Dongfeng Motor Corp., SAIC Motor Corp., Stellantis, Volkswagen Group, Volvo Car Group, Great Wall.
#2	LG Energy Solution Ltd. (LGES)	Lithium-ion	14%	Korea	General Motors, Groupe Renault, Stellantis, Tesla, Volvo, VW Group, Ford, Hyundai, Chevrolet.
#3	BYD Co., Ltd	Lithium-ion	12%	China	BYD, Ford.
#4	Panasonic	Lithium-ion	10%	Japan	Tesla, Toyota.
#5	SK Innovation Co., Ltd.	Lithium-ion	7%	Korea	Daimler, Ford, Hyundai, Kia.
#6	Samsung SDI Co., Ltd.	Lithium-ion	5%	Korea	BMW, Ford, Stellantis, VW Group.
#7	China Aviation Lithium Battery Co., Ltd. (CALB)	Lithium-ion	4%	China	GAC Motor, Zhejiang Geely Holding Group Co.
#8	Guoxuan High-Tech Power Energy Co., Ltd.	Lithium-ion	3%	China	Chery Automobile Co., SAIC, VW Group.
#9	Sunwoda Electronic Co., Ltd.	Lithium-ion	2%	China	Dacia Spring Electric, Renault K-ZE City.
#10	SVOLT	Lithium-ion	1%	China	Great Wall Motors.

Lithium-based batteries opened a new era for high-energy and high-power batteries, which are gradually replacing older battery technologies like lead-acid and nickel-based ones *(Demir-Cakan, Palacin, & Croguennec, 2019)*. Several battery technologies were explored and emerged in the late 1960s when traditional batteries failed to satisfy the booming demands for portable energy storage. At the moment, lithium-ion batteries are used in EVs. Table 5 summarizes the names of batteries, cell chemistry, manufacturers, EV models, and driving range (km) *(Nemeth, Schröer, Kuipers, & Sauer, 2020; Trimboli, de Souza, & Xavier, 2021)*.

Table 5. Specifications of different types of popular EV batteries, cell chemistries, capacity, and driving range by various EV battery manufacturers and EV models.

Battery	Cell Chemistry		EV Battery Manufacturers (Producer)	EV Model	Voltage (V)	Specific Energy ($Wh.Kg^{-1}$)	Capacity (Ah)	Energy Density ($Wh.L^{-1}$)	Energy (kWh)	Range (km)	References
	Anode	Cathode									
Li-ion (Cobalt-medium)	Carbon (C)	NCM	Panasonic	VW e-Golf (2015)	3.65 ~ 4	130 ~ 241	25	215	24	135-190	*(Chikkannanavar et al., 2014; W. Li et al., 2020; Yong Li et al., 2014; X.-G. Yang et al., 2021), (R. Zhang et al., 2018), (Murdock, Toghill, & Tapia-Ruiz, 2021; Schmuch, Wagner, Hörpel, Placke, & Winter, 2018)*
			LG Chem	Chevrolet Bolt (2016)			56	393	60	383	
			LG Chem	Renault Zoe (2017)			59	466	52	390	
			Panasonic, LG Chem	VW ID.3 Pro S (2020)			25 56 59	215 393 466	82	550	
				ByD Qin Pro EV					69.5	520	
				NIO ES6 Standard					84	490	
				BAIC EU5 R550					60.2	460	
		NCA	Panasonic,	Tesla S (2012)	3.6~ 3.65	200~ 310	3.4	673	~ 100	595	
	C or SiOC,	NCA	Panasonic,	Tesla X (2015)			3.4	673	~ 100	525	
				Tesla 3 (2017)			4.75	683	~ 75	500	
	Si-C or SiO_x-C	NCA	SAFT, LG Chem	Tesla Y (2020)			4.75	683	75~ 100	480~ 595	
	LTO	NCM	Toshiba	Honda Fit EV (2013)	2.3~ 2.5	89	20	200	20	130	
		NCA				70-85					
Li-ion (Cobalt-poor/free)	LTO	LMO	Toshiba	Honda Fit EV (2013)	2.3~ 2.5	70~85	20	200	20	130	*(D. Wang et al., 2021), (Chikkannanavar et al., 2014; W. Li et al., 2020; Yong Li et al., 2014; X.-G. Yang et al., 2021), (R. Zhang et al., 2018), (Jiang, Danilov, Eichel, & Notten, 2021)*
	Carbon (C)	LMO	LG Chem, GS NEC, Yuasa	Mitsubishi i-MIEV (2018)	3.7~ 4.0	100~ 150	50	218	16	100~ 160	
		LMO, NMC	Li Energy Japan	Mitsubishi i-MIEV (2018)	3.7	109	50	218	16	100~ 160	
		NCM	Samsung SDI	Fait 500c (2013)	3.65	172	63	312	24	140	
		LMO	Samsung SDI	VW e-Golf SEL (2016)	3.7	185	37	357	35.8	201	
		NCA	Samsung SDI	BMW i3 (2017)	3.7	189	94	357	33~ 42.2	183~ 246	
		NCM	Samsung SDI	BMW i3 (2017)	3.7	189	94	357	33~ 42.2	183~ 246	
		LMO	AESC	Nissan Leaf (2015)	3.75	155	33	309	30	172	
		NCA	AESC	Nissan Leaf S Plus	3.75	167	40	375	62	364	
		LFP	A123,	Chevrolet Spark		90~ 130	27	144	19	132	

			Valence Tech, BYD	BAIC EC220	3.2~ 3.3				19	206	
		LFP	BYD	BYD Tang Electric	3.2	140~ 166	216	279	86	505	
		LFP	LG Chem	Chevrolet Spark EV	3.75	90	27	144	19	132	
Lithium Nickel Manganese Cobalt Oxide (NMC)	C	NMC721	LG Chem	Audi e-tron GT	3.65	263	64.6	648	85	392	*(Senthil et al., 2022), (Chikkannanavar et al., 2014; W. Li et al., 2020; X.-G. Yang et al., 2021), (Nemeth et al., 2020), (Clément, Lun, & Ceder, 2020)*
		NMC722	LG Chem	Audi e-tron GT	3.65	148	129.2	648	93	472	
		NMC721	LG Chem	Audi Q4 e-tron SUV	3.65	156	78	648	77	305	
		NMC622	LG Chem	Chevrolet Bolt	3.75	151	55	228	65	417	
		NMC622	LG Chem (Umicore)	Hyundai KONA Electric	2.30	142	60	164	64	484	
		NMC811	LG Chem	Kia EV6-LR AWD	3.56	163	11.2	230	78	303	
		NMC622	LG Chem	Nissan LEAF E Plus	3.56	151	56.3	230	62	364	
		NMC532	AESC	Nissan LEAF	3.65	130	56.3	205	39	240	
		NMC721	LG Chem	Renault Zoe e-tech electrique	2.08	160	130	166	52	395	
		NMC	LG Chem	Smart fortwo Electric	3.65	152	52	316	18	145	
		LMO, NMC	LG Chem	Ford Focus Electric	3.70	126	16	144	36	160	
		NMC532	LG Chem	Volvo XC40	3.65	152	52	316	78	292	
		NMC111	Samsung SDI	VW e-Golf	3.70	185	37	185	36	300	
		NMC721	LG Chem	Volkswagen ID.3	1.85	164	145	164	58	350-544	
	LTO	NMC	Toshiba	Honda fit EV	2.30	89	20	200	20	130	
	C	NCM622	Samsung SDI	BMW i3	3.68	148	94	648	38	178	
Lithium ion polymer Battery [LPO]	C	NMC	LG Chem	Hyundai ioniq 5-LR AWD	2.30	142	60	164	77	488	*(Chacko & Chung, 2012; R. Zhang et al., 2018), (Trimboli et al., 2021), (Chang, Yang, Zhu, He, & Zhou, 2022; Yi et al., 2022)*
		NMC811 +	SK Inno-vation	Kit Niro	3.56	250	180	164	64	370	
		NMC622	SK Inno-vation	Kia Soul EV	3.56	250	180	164	64	391	

6 Conclusion

This overview comprehensively looked at conventional, contemporary, and future battery technologies for electric vehicles, including the most crucial elements, such as the main component materials, operational characteristics, theoretical models, and cost analysis. Additionally, concentrated attention was given to the electromechanical process of charging and discharging and the latest advancements of the most recently develop various types of batteries used for EVs in this article. After studying several recent articles in this field, it can be concluded that the choice of battery technologies depends on the parameters that make it optimal for the intended application.

The lead acid (PbO_2) batteries are comparatively inexpensive, they are commonly used, especially for automotive systems that operate at ambient temperature and are not sensitive to the memory effect. However, this technology is quite polluting, the number of cycles is quite low (around 500) and its energy is limited. The Nickel Metal Hydride (NiMH) batteries, unlike previous types, are non-polluting. They can store more energy and generally have better performance, even if their self-charging is more disabled and their life span is shorter in the number of cycles. They hardly detect full charge and do not support overflow charging. They are inefficient, have increased power and energy densities, heavy and technologically outdated.

In recent years, significant progress has been made in the development of Li-ion batteries such as LCO, NMC, LMO, NCA, LFP, LTO, LPO, and so on for use in EVs. Due to their superior qualities, such as high specific energy, little memory effect, minimal self-discharge, and a long lifespan, Li-ion batteries would be continuously dominate the onboard power battery market. They have higher mass and volume energies. In addition, they have very good charge/discharge performance, very low internal resistance, and self-charging percentage. Li-ion batteries are expensive to replace. In fact, the cost of a battery is almost half the price of an EV.

In the near future, there could be cheaper and lighter batteries with more electric power range than lithium-ion battery packs. Several Advanced battery technologies like Li-O_2, Li-Si, Na-ion, Si-based anode, Zn-ion, Li-S and ASSB batteries are prepared for the next generation of electric vehicles. Commercial appliances are more commercially successful, technically dependable, and thermally stable. But they have yet to be adopted by the EV industry.
Currently, most electric vehicle brands in North America use lithium-ion batteries made of cobalt, graphite, nickel or aluminum. Tesla uses lithium-ion batteries that have a lifespan of 300k to 500k miles. In addition, the battery range of the latest fully charged electric vehicles is from 300 miles to 500 miles.

EV battery technology is gradually improving. Back in the '90s, the best electric vehicles with batteries could cover a range of 50 to 100 miles when fully charged. Today, the technology has advanced, and some electric vehicles can travel nearly 500 miles on a full battery charge. In the next decade, there could be electric vehicles that can travel more than 1,000 miles on a full battery charge.

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Biography

Oluwafemi Emmanuel Oni is a postdoctoral researcher in the Electrical and Electronic Engineering Science department at the University of Johannesburg, South Africa. He received his BSc (Honours) Degree in Electrical and Electronic Engineering from Ekiti State University, Ado Ekiti, Nigeria, in 2013 and his MSc and PhD in 2017 and 2021 respectively. He was a system and maintenance engineer at Egbin Power Thermal Plant, Lagos, Nigeria, in 2012 and at Omotosho Power Plant, Ore, Nigeria, in 2013/2014. He is currently a postdoctoral research fellow at the University of Johannesburg. His research includes power systems stability analysis using High Voltage Direct Current transmission scheme, integration of renewable energy into the grid using a multi-terminal HVDC scheme, and smart grid systems using FACTs. Dr. Oni's award and honours include MTN Foundation, ETISALAT, and Ekiti state scholarships.

M. M. Mostafa Almadani is a currently a PhD student in the Department of Electrical and Electronic Engineering Science, University of Johannesburg, South Africa. He is doing PhD in Electrical and Electronic Engineering with renewable energy and electric vehicle (REEV). He obtained M.Eng degree in Computer Science and Engineering and B.Eng degree in Mechatronics Engineering from International Islamic University Malaysia, Malaysia. He has ten years of industrial work experience in the textile industry as a maintenance and utility manager. He also has relevant experience in research and community services. His research interests are Renewable Energy Technologies, Electromobility, Smart Energy Management, Energy Efficiency, Smart Grid, 4IR in Energy System.

Omowunmi Mary Longe is an Electrical and Electronic Engineering Science Associate Professor at the University of Johannesburg, South Africa. She is also the Chair of the department's Smart Power and Energy Systems Research Group. She received her Doctor of Engineering (D.Eng) in Electrical and Electronic Engineering Science in 2017 from the University of Johannesburg. Her M.Eng and B.Eng degrees were obtained in Electrical and Electronics Engineering in 2011 and 2001, respectively from the Federal University of Technology, Akure, Ondo State, Nigeria. She is a Senior Member of the Institute of Electrical and Electronics Engineers (SMIEEE), and Senior Member of the South African Institute of Electrical Engineers (SMSAIEE). She has published more than forty papers in referred journals and conference proceedings. She is also a reviewer for ISI-listed journals and referred professional conferences. Her research interests include renewable energy technologies, microgrid optimization designs, mobility, energy poverty, demand-side management, distributed energy generation and storage, and smart energy management**.**