A Review on Recent Progress of Batteries for Electric Vehicles

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Abstract
The progress of the development of electric vehicles over the decades has been improving in a fast pace. After the outbreak of oil shortage and the impact of greenhouse gaseous released from the internal combustion engine vehicles to the environment in 1970s, society started to work on investigating the usage of environmentally friendly vehicle that uses alternate energy. Out of all the solutions, electric vehicle could be the answer to the challenges addressed. As battery serves a large part in the industry of electric vehicles, this review paper focuses on the recent progress of battery for electric vehicles. This review paper discussed about the oldest type of rechargeable battery, lead-acid battery to the recent commonly used battery, which is the latest technology of battery, lithium-ion battery. The materials of battery components, battery parameters, battery pack design and cell design as well as the sustainable issue of batteries for lead-acid battery, nickel metal hydride battery (NiMH), ZEBRA battery and lithium ion battery (Li-ion) were described and examined in exquisite details. The future development of the batteries such as rechargeable magnesium battery and sodium ion battery were also evaluated.

Keywords: Electric Vehicles; lead-acid battery; nickel-based battery; ZEBRA battery; Lithium based battery

1.0 INTRODUCTION
Due to public attention of the limited amount of fuel energy in the world and the emission of greenhouse gaseous by the internal combustion engine vehicles, people started to look for environmentally friendly vehicles that can be powered using alternate rechargeable energies. As electricity is one of the sustainable energies, the concept of vehicles using electricity to power up the car was introduced. Although electricity is the sustainable energy to power up the motors of the vehicles, the concept of an electric vehicle was not introduced to the world until the year of 1859. In the same year, the rechargeable battery named lead-acid battery was first conceived by Gaston Plante [1]. Batteries play an important role to the evolution of the electric vehicles as it is a must for the electric vehicles to carry a portable item that stores electricity in order to have the electricity supply to its motor.

Figure 1. The first invention of electric car by Gaston Plante

1.1 ELECTRIC MOBILITY
Electric mobility is one of the fields that uses rechargeable energy which is the electricity. Electric mobility includes all the street vehicles using electric motor that rely on the electricity power either fully or partially. Vehicles using purely electric motor (Electric Vehicles – EV), vehicles using small combustion engine and electric motor (Range Extended Electric Vehicles – REEV) as well as vehicles using conventional internal combustion engine system and electric propulsion system (Hybrid Electric Vehicles – HEV) are considered as electric mobility. The automotive vehicles created in the industry of electric mobility use electricity energy in the rechargeable batteries to power up their systems in order to function. As the automotive vehicles use electricity to power up their electric motors, there are no emission of greenhouse gaseous by the automotive vehicles as there are no combustion occurred in the system unlike the usage of internal combustion engines [2].

1.2 ELECTRIC VEHICLE
The electric vehicle, which is as known as EV, is powered purely by its electric motor that gains energy from the source of electricity. Electric vehicles are not something new to today’s world, the first electric car was invented back in 1859, which is 160 years ago from 2019. The electric vehicles lost the game in the industry of automobiles to the internal combustion
engine vehicles over the years. According to the US automobiles sales data in 1900, among 4800 automobiles sold, the percentages of electric vehicles, internal combustion engine vehicles and steam-power vehicles were 38%, 22% and 40%. At that time, the demand of electric vehicles is considerable. Frantically, the popularity of electric vehicles did not last and the demand of it almost wiped out just 30 years later. The demand of electric vehicles in 1930 was almost replaced by the demand of internal combustion engine vehicles. However, due to the announcement of oil shortage in 1970s as well as the concerns of environmental and awareness of air quality in the surrounding in 1980s arise, people starting to rekindle their interests in electric vehicles. The development of the electric vehicles accelerated as people wanted to save the environment [3]. Norway is one of the many countries in the world that highly promotes the usage of electric vehicles to its nations. The government of Norway promotes electric vehicle usage by adapting measurements like exemption of roadway tolls, accessing infrastructure of charging stations, limited lanes for public bus and more [4].

The usage of using electric vehicles can certainly bring several benefits to the humankind society. One of the most obvious advantages that people using electric vehicles is the reduction of greenhouse gaseous emission. Electric vehicles that powered mainly by the electric motor do not require combustion to run the vehicles like internal combustion engine vehicles. Without combustion, there is zero emission of greenhouse gaseous by the electric vehicles.

However, there is also downsides of using electric vehicles than using internal combustion engine vehicles. The downsides of using electric vehicles including the lengthy time required for the electric vehicles’ batteries to recharge. By using electric vehicles, the users required to charge the vehicles exactly just like how the internal combustion engine users needed to refill the fuel. Unlike refilling the fuel, the time required to recharge the batteries in the electric vehicles is longer. The time-consuming batteries recharging session could be quite inconvenience to the electric vehicles’ users.

1.3 TRACTION BATTERY

Traction battery was one of the most important components of the electric. Mainly road vehicles, locomotives, industrial trucks and mechanical handling equipment use the traction batteries as power resources. It is also possible to refer to the rechargeable traction battery as the electric vehicle battery (EVB). The traction batteries, unlike the auxiliary batteries, support the entire electric vehicles instead of just providing the energy needed to start the engine for the vehicles. The lead-acid battery, the nickel-cadmium battery (Ni-Cd), the nickel-metal hydride battery (NiMh) and the lithium are examples of the major traction batteries.

1.4 LEAD-ACID BATTERY

Lead-acid battery was invented in 1859 by Gaston Planté as the world’s first rechargeable traction battery. The lead-acid was the first type of rechargeable battery in the world that was commercially used especially in the industry of automobiles [5]. The lead-acid battery was modified by Camille Alphonse Faure in 1881 and the performance and capacity of the modified lead-acid battery has improved by using the lead grid lattice. The manufacturing processes of the lead-acid batteries were also made easier after the modification of lead-acid batteries by Camille Alphonse Faure. Although the lead-acid battery was invented 160 years ago from 2019, it is still contributing widely in the field of automobiles considering its cheap cost [6].

1.5 NICKEL CADMIUM BATTERY (NICD)

Nickel Cadmium Battery has been widely used by the society and intended to replace lead-acid battery especially the automobiles manufactured in Europe. The usage of Nickel Cadmium battery in the electric vehicles is developed in 1980s and 1990s. The Nickel Cadmium battery is well known for its good battery cycle life. Unfortunately, due to its relatively low range and uncompetitive selling price, the market of Nickel Cadmium battery did not expand [7].

1.6 NICKEL METAL HYDRIDE BATTERY (NIMH)

The usage of hydrogen inserted in metallic alloys instead of cadmium at the negative electrode, the Nickel Metal Hydride battery is considered an advanced version of the Nickel Cadmium battery. The Nickel Metal Hydride battery is constantly sealed to prevent hydrogen from leaking. Due to the Nickel Metal Hydride battery’s significant improvement in energy density, it replaces Nickel Cadmium in the application of electric vehicles. The usage of Nickel Metal Hydride battery did not get commercialized in the 1990s as the newer technologies of battery were introduced very soon after the Nickel Metal Hydride was developed [7].

1.7 LITHIUM-ION BATTERY

Rechargeable lithium-ion batteries were developed and introduced in the 1990s to the world with a significant weight advantage over other battery systems. Lithium-ion battery, known as one of the most outstanding quality in the new electrochemical industry. It is one of the most used and widespread batteries used by electric vehicles today [8]. The Lithium-ion battery’s weight advantages make it competitive with other battery systems. Because of its high specific energy, the lithium-ion battery has a relatively greater travel distance, which is about three times greater than the mileage of the lead acid battery [9].

In the automotive industry, the Lithium-ion battery has obvious advantages as it has a long cycle life, high energy capacity and high efficiency. Lithium-ion batteries are extremely likely to contribute more to the current markets and the lives of people as the development of new products, innovations and strategies continues to advance[10].
2.0 ELECTROCHEMISTRY

Batteries with the ability to store energy electrochemically have achieved many of today’s advancements. Batteries are widely used in a variety of devices and machinery; however, it is the complex chemistry occurring within the battery cells that enables the modern conveniences. Batteries are composed of two terminals which are positive and negative terminals or cathode and anode, electrolyte and casing to hold all the components within. The electrolyte is added to divide anode and cathode but allowing the ions to flow. Battery undergoes an electrochemical reaction where the conversion of chemical energy into electrical occurs when a load or power supply is connected between the terminals [11]. In this reaction, anode undergoes oxidation which donates or releases electrons through the terminal. Meanwhile, cathode undergoes reduction where the electrode reacts with the ions and accepts the electrons given by the anode. In short, the anode releases its electrons and, the cathode accepts and uses them.

Currently, there is a few different types of rechargeable batteries available to be used in electric vehicles. The batteries are enhanced and transformed to have better quality and chemical properties as the time passes by. The evolution of the batteries can be arranged in the sequence of lead-acid battery, nickel-metal hydride battery, sodium-nickel chloride battery and a lithium-ion battery. Today, lithium-ion batteries have dominated the major commercial market. Therefore, a brief description of the electrochemistry in all rechargeable batteries used in electric vehicles and the recent progress on the materials selection for the electrodes used in lithium-ion battery will be discussed.

Lead-acid batteries are assembled with multiple individual cells covered with layers of lead alloys plates drenched in an electrolyte. In each cell, there is a plate with lead dioxide as positive electrode, a metallic lead plate as negative electrode. Both plates are separated by an insulated separator and immersed in an electrolyte with the composition of approximately 65% H₂O and 35% sulphuric acid [12].

In the charge and discharge condition of lead-acid battery, huge chemical processes take place for the conversion of energy. The diluted sulphuric acid molecules dissolve and convert into positive hydrogen ions (2H⁺) and negative sulphate ions (SO₄²⁻). If a DC supply is connected to the terminals, the positive hydrogen ions (2H⁺) moved towards the negative electrode. Also, the negative sulphate ions (SO₄²⁻) are attracted by the electrode that connected to the positive electrode. The hydrogen ions receive two electrons at the cathode and form a hydrogen atom. This atom reacts with the lead sulphate (PbSO₄) to form a product with the composition of lead (Pb) and sulphuric acid (H₂SO₄).

Nickel-metal hydride batteries in a solid hydride cycle store hydrogen as an active component. The negative electrode of the nickel-metal hydride battery is a hydrogen storage medium that releases the hydrogen when charging and discharging and enables the electrochemical reaction to take place [3]. This electrode is made from metal hydride which is usually the rare earth mixture of lanthanum alloy [4]. The nickel hydroxide Ni(OH)₂ serves as the positive electrode in the battery cell.

Oxidation and reduction take place at both electrodes through an electrolyte which consists of 30% KOH in water.

In charging condition, oxidation took place in nickel hydroxide Ni(OH)₂ electrode. Hydroxyl ion reacts with nickel hydroxide Ni(OH)₂ and form nickel oxyhydroxide (NiOOH) and water. On the other hand, the MH electrode which represents the hydrogen-absorbing alloy is reduced. Water is separated into hydrogen which again reacts with the metal to form MH in the cathode. The nickel hydroxide Ni(OH)₂ served as positive electrode to promote the reversibility in electrochemical reaction with nickel oxyhydroxide (NiOOH). The stream of the nickel-metal hydride battery charging and discharging is therefore in the opposite direction.

Sodium-nickel chloride battery used a negative electrode which is composed of liquid metal sodium and a mixture of nickel (II) chloride (NiCl₂) and iron (II) chloride (FeCl₂) as the positive electrode. A ceramic solid metal, Na-β” alumina (Na₂Al₁1O₁₂) is used as an electrolyte to separate both electrodes away. It prevents the direct chemical reactions between the electrode constituents but allowing the sodium ions to flow between the electrodes. Also, the second electrolyte of molten sodium tetrachloro-aluminate (NaAlCl₄) is used in helping the transportation of sodium ions to the positive electrode [5]. The constitution of a cell for sodium-nickel chloride battery is shown as Figure 2.

![Figure 2. The constitution of a cell [5]](image)

In the discharged state, the mixture of metal chloride phase is fabricated in the positive electrode from a mixture of aluminium, iron, nickel and common salt. These metals are oxidized by the initial charge and the salt is decomposed into sodium and chloride ions. The chloride ions react and combine with the oxidized metals to form metal chlorides. The cell discharging process is a reversible chemical reaction.

Lithium-ion batteries relied on the insertion of reactions from both negative and positive electrodes where lithium ions act as...
the charge transporting system to store energy. In 1991, Sony became the first to manufacture and sell lithium-ion batteries [6]. The idea of the reversibility in the movement of lithium ion between the electrodes in the battery is first developed by Armand which used different intercalated materials for two electrodes [7]. It enables the lithium ions to flow back and forward among two electrodes. Goodenough laboratory discovered the reversibility of the NaFeO2 crystal structure in deintercalation of the lithium ions at relatively high potentials. Metals, including magnesium, aluminium, iron, etc. with the mixture of nickel and cobalt were discovered later to have the similar ability and adopted the lithium cobalt oxide (LiCoO2) to be the active positive materials for Sony’s lithium-ion battery. Lithium cobalt oxide (LiCoO2) is the first and most common form of layered transition metal oxide cathodes. It is very suitable to be a cathode material because it has high theoretical specific capacity, volumetric capacity, discharge voltage, and good cycling performance. Meanwhile, most lithium-ion batteries’ negative electrode consists of graphite or lithium titanate (Li4Ti5O12) and certain materials still under development, namely lithium metal and Li-Si alloys [8]. The electrolyte is used which is usually created to allow the movement of ions between electrodes with a mixture of organic solvent and lithium salts. Besides, a separating membrane or separator is used to separate both electrodes away from each other but, allowing the electrode to flow while eliminating the chances of internal short circuit. **Figure 3** shows the schematic construction of a battery cell of the lithium-ion battery.

![Figure 3. Schematic construction of a Li-ion battery cell [8]](image)

Based on **Figure 3**, a separator is integrated to avoid the direct contact between two electrodes. The electrons flow from negative electrode to the load, and then went to the positive electrode through the current collector when it acts as a galvanic device. Concurrently, the lithium ions (Li+) flow from negative electrode to positive electrode via the electrolyte so that the electroneutrality can be maintained. At present, there are many choices of materials that could be selected to be the positive and negative electrodes, and the electrolyte in the lithium-ion battery.

### 2.1 CATHODE

Intercalation compounds which enable the lithium ions (Li+) to diffuse out and in are generally used as the positive electrodes. These compounds include lithium cobalt oxide (LiCoO2), lithium nickel oxide (LiNiO2), lithium manganese oxide (LiMn2O4), lithium iron phosphate (LiFePO4), nickel manganese cobalt oxide (LiNi0.5Mn0.5Co1−x−yO2), and lithium nickel cobalt aluminium oxide (Li(Ni0.8Co0.2Al0.1−x−y)O2). Lithium cobalt batteries are very reactive which cause it to have low thermal stability and unsafe to use if it is not being monitored. The limitation of resources in cobalt also makes it be more expensive which decrease the feasibility to be implemented into electric vehicles. However, it is used to create high energy to power the Tesla Roadster and Smart Fortwo electric drive. Lithium nickel oxide (LiNiO2) is recognized to be a low-cost material for the high voltage batteries where it has a high theoretical capacity with a value of 250 Ah kg⁻¹. But the self-passivation layer which formed on the surfaces cause difficulties in the handling of this material. This material has a complex manufacturing process due to its stoichiometric properties and a lot of requirements needed to be met. Thus, Lithium nickel oxide (LiNiO2) is somewhat a less practical electrode materials used in rechargeable batteries. Lithium manganese oxide batteries (LMO) also have low internal resistance and good current handling due to their architecture that forms a three-dimensional spinal structure that could improve the ion flow between the electrodes. The chemistry within the battery cells provide better thermal stability. However, it has roughly thirty-three percent lower capacity and lower life span than lithium cobalt oxide. Most of the lithium manganese oxide batteries are blended with the lithium manganese cobalt oxide (NMC) to enhance its specific energy and extend its life span. Nissan Leaf, Chevy Volt and BMW i3 had been manufactured in the past with the LMO-NMC batteries [9]. Besides, a researcher in the University of Texas had discovered which phosphate materials are selected as the positive electrodes in the lithium-ion battery in 1996. Lithium iron phosphate (LiFePO4) was then introduced, which has improved electrochemical efficiency with low cell resistance and high current rating. Phosphate helps to stabilize the electrode against overloading and increase heat tolerance which restricts material breakdown [9]. Lithium iron phosphate (LiFePO4) battery is less likely to experience the thermal runaway as it has a wide range of operating temperature. This battery also has higher self-discharge as compared to other lithium-ion batteries. However, the moisture is an issue of this battery where it significantly limits the its lifetime. Additionally, lithium nickel manganese cobalt oxide (Li(Ni0.8Mn0.2Co1−x−y)O2) electrode is designed to increase its high specific energy either power with high density. This electrode is composed of nickel and manganese where nickel has high specific energy but low stability; manganese helps in forming a spinel structure which achieves low internal resistance but...
provides low specific energy. Nickel is used to combine with the manganese enables to enhance the strength of each other’s which make the NMC to be one of the most effective lithium-ion system. This battery is currently high demand in the current commercial market due to its high specific energy and excellent thermal properties. Lastly, lithium nickel cobalt aluminium oxide (Li(Ni_{x}Co_{y}Al_{1-x})O_2) battery is somewhat similar to NMC which offers high specific energy, power and a long life span. This battery is not as safe as other batteries mentioned above and require a special safety monitoring measure before integrating it into the electric vehicles. It is also more expensive to manufacture which limits their viability to be used in a wide variety of application.

2.2 ANODE
There are two types of negative electrodes that are used in lithium-ion batteries, namely lithium titanate and carbon-based electrode. New types of negative electrodes are currently under development, including lithium metal, lithium-metal alloy, lithium-silicon alloys and conversion electrodes. First of all, carbon and usually synthetic graphite are still used as the negative electrode in the lithium ion batteries because they have high specific capacity, low average voltage and high energy efficiency in the round trip [10]. It is generally used and an excellent alternative for the electrode as it is a material that is low cost, available and safe from toxic. However, if the carbon reacts with the atmospheric oxygen or experiences a thermal runaway event, the electrode may catch on fire. Furthermore, in the traditional lithium ion battery, lithium titanate was used to substitute graphite as the negative electrode which shapes into a spinel shape. The appropriate counter-electrode with lithium titanate is lithium manganese or lithium manganese cobalt oxide. There is no volume difference in the spinel lithium titanate during lithiation that extends the electrode’s operational life. Because of its lithium diffusion coefficient, it has weak electrical conductivity and poor performance at high power rates, but this can be enhanced by increasing the duration of the transport path of lithium ion by correct nano-structuring. Lithium titanate batteries are integrated in the Mitsubishi’s i-MiEV electric vehicle. Therefore, lithium metal is a favorable negative electrode in the lithium ion battery with large capacity and low negative electrochemical potential where the electrode size will decrease the negative electrode mass due to the magnitude order. However, during lithium plating or stripping, the growth of metallic dendrites in the lithium metal electrode may cause short circuit. The design of this electrode progresses and aims to create a stable lithium metal electrode that could boost electric vehicle efficiency [11]. In addition, alloy-based electrodes made of lithium-alloy metals have a higher specific capacity than conventional graphite electrodes. Throughout phase transitions, accommodation of a large amount of lithium is followed by a major density shift in the host material. The mechanical strain allows the metal electrode to break and crumble during the alloying or de-alloying processes and the lack of capacity that used to hold charge. The electrochemical method experiments that are partly reversible to form alloys between several metals and lithium proceed. In comparison, lithium-silicon alloy has a greater potential effective strength than metallic lithium in its completely lithiated structure. In this electrode chemistry, during the transition between Si and Li15Si4, there is a significant volumetric change in the electrode material that creates high internal strain in the active materials [12]. The internal strain could cause the Si material to crack and eventually disintegrate, resulting in a significant fade in reversible capacity. In contrast, Si has strong electrical resistivity and poor lithium diffusivity. The composite electrodes made of nanostructure Si have a high capacity to withstand volume expansion [13], and boost mechanical and electrical properties through the use of a highly doped Si embedded in conductive matrices. The issues mentioned to date have prevented the practical use in electric vehicles of silicon-based electrodes. Finally, batteries that use the conversion-type electrodes have a higher density of energy storage but undergo a substantial fading in power than the one with intercalation-type electrodes. In the conversion electrodes there is an actual chemical reaction where it is opposed to the only intercalation of the lithium ions into a host material's lattice.

3.0 BATTERIES PARAMETERS
The most important core for the electric vehicle is the traction battery component. Without the main battery, the electric motor cannot perform its function relatively. Lately, EV battery manufacturers were keeping developing new type of battery for electric vehicle, innovating and improving the existing batteries to increase the efficiencies for each parameter.

3.1 BATTERY SPECIFIC ENERGY, SPECIFIC POWER, ENERGY DENSITY, WEIGHT AND SIZE
At the early stages of the EV generation, Pb-Acid has used as the primary core to power the EV. Pb-Acid battery basically can be identified as two primary categories: Starting battery and Deep-Cycle Battery [22]. Deep-cycle type such as VRLA, AGM and Gel was used for EV as it has a greater energy capacity and durability. In fact, Pb-Acid batteries was unable to generate voltage itself; instead they received or stored a charge from another origin. Therefore, Pb-Acid batteries are referred to as storage batteries as they carry just one charge. The size and amount of electrolyte of the battery plates will determine how much charge lead acid batteries can be stored. A battery's amp-hour (Ah) or watt-hour (Wh) rating is described as the size of the storage capacity for all types of batteries [23]. The Pb-Acid battery has a low specific energy and energy density with a value of 35-40 Wh/kg and 80-90 Wh/L [24], in which the early electric vehicle required a large amount of battery size in powering the vehicle that resulted in incremental of curb weight of the electric vehicle at the same time. According to study by Ahman, an EV battery should be able to store up 30 kWh capacity to afford the vehicle an acceptable range [25]. In order to generate 1 kWh electrical energy, an approximate 30 kg lead acid battery was required. Assuming the initial electric vehicle consumed 20 kWh/100 km, for the Pb-Acid battery to be capable to support the electric vehicle, 20 packs of batteries to travel 100 km which consisted total of 600 kg mass from the batteries itself. The typical Pb-Acid battery has a specific power of 285 W/kg [26]. Specific power, or gravimetric power density can be defined as the
loading capability for a battery. Batteries made for EV application usually have a low specific energy or energy density in combination with a high specific power. A higher specific power value indicate that more energy can deliver to the electric motor to drive the vehicle which means greater acceleration in a short time.

It did not take long for people to recognize that lead-acid type battery was not suitable for powering the EV for a long-term period due to low energy densities, sensitive to temperature and life cycle. Soon, a new nickel-based battery was invented by Waldemar Jungner in 1899 [27] which replaced the lead-acid battery as the power source in EV. Unlike Pb-Acid, the nickel metal hydride (Ni-MH) uses an alkaline electrolyte – a concentrated potassium hydroxide aqueous solution. Some common type of nickel-based batteries consisted Nickel-Iron (Ni-Fe), Nickel-Cadmium (Ni-Cd), Nickel-Zinc (Ni-Zn) and Nickel-metal hydride (Ni-MH). Because of the short life cycle and low specific strength characteristics, the Nickel Iron and Nickel Zinc batteries were not really applied on the EV application [28]. The battery which commonly used for EV was the Ni-MH type as it possessed higher specific energy and energy density compared to Pb-Acid battery with a value of 50-70 Wh/kg and 100-140 Wh/L [28]. Ni-MH battery was chosen over the Ni-Cd is because it has relatively higher specific energy and density content and Ni-MH did not contain toxic metals which was cadmium. Besides, research also had shown that Ni-MH provided 40 % higher specific energy than the standard Ni-Cd [27]. Therefore, most of the EVs has adopted the Ni-MH battery technology as it can greatly lower the battery packs total weight and improve the energy consumption efficiency. It also has a lower energy density value which allow the battery system to be contained within a smaller space. In order to generate 1 kWh using Ni-MH battery, an approximate 20 kg of Ni-MH battery was required. Comparing to the lead-acid, the battery mass can say to be reduced by a 33 %. However, the used of Ni-MH battery in EVs has reached a bottleneck as its practical specific energy limitation can only achieved until 75 Wh/kg [29]. A typical Ni-MH battery has a specific power of 200 W/kg [26]. Other than that, Ni-MH battery also having self-discharge problem. In the first 24 hours right after charge, the self-discharge rate of the Ni-MH battery has a value of twenty percent and 10 percent per month thereafter [27].

Later, there was another alternative battery that can be used for power the EV which named as sodium-nickel chloride (ZEBRA) or ‘Zero Emission Battery Research Activity’. This technology was first invented in South Africa during the 1970s and 1980s [30]. This type of battery has a remarkably specific energy and energy density with a value of 100 Wh/kg and 160 Wh/L [31]. The specific power rating and power density for ZEBRA battery is 170 W/kg and 250 W/L respectively [32]. However, the optimum operating temperature (300 °C) for ZEBRA battery requires pre-heating before use, which consumed considerable energy if parked regularly for long periods. Therefore, it is more suitable to applications where the EV is being used continuously such as the urban public transportation.

Finally, the revolution of the battery reached the stage where the lithium-ion based battery took over the place. The current primary sources for almost every EV around the world are using the Li-ion based battery. Lithium has the smallest value of weight among of all metals, with the greatest electrochemical potential and possessed the largest specific weight and high density of energy [33]. Li-ion based battery basically consisted of two types, those with liquid (Li-ion-liquid) and those with polymer electrolyte (Li-ion-polymer) while the liquid-ion type is preferable for EV purpose. There are three different combination of materials for the liquid Li-ion type battery which are Lithium Iron Phosphate (LiFePO4), Lithium Manganese oxide (LiMn2O4) and Lithium Cobalt Oxides (LiCoO2). Li-ion based batteries that used for EV applications normally has a specific energy of 150-200 Wh/kg and an energy density of 250-400 Wh/L [34]. The specific power rating for a typical liquid Li-ion battery used for EV application has a value of 260 W/kg [26]. In order to generate 1 kWh using Li-ion battery, an approximate 7 kg of Li-ion battery was required. Comparing to the Pb-Acid and Ni-MH, the battery mass can say to be reduced by 77 % and 65 % for 1 kWh capacity.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Specific Energy (Wh/kg)</th>
<th>Energy Density (Wh/L)</th>
<th>Specific Power (W/kg)</th>
<th>Mass of battery for 1 kWh/100km</th>
<th>Mass reduction compared to previous battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-Acid</td>
<td>35-40</td>
<td>80-90</td>
<td>285</td>
<td>500 – 600 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>50-70</td>
<td>100-140</td>
<td>200</td>
<td>300 – 400 kg</td>
<td>36.36 %</td>
</tr>
<tr>
<td>ZEBRA (Na-NiCl2)</td>
<td>100</td>
<td>160</td>
<td>170</td>
<td>200 kg</td>
<td>42.86 %</td>
</tr>
<tr>
<td>Li-ion</td>
<td>150-200</td>
<td>250-400</td>
<td>260</td>
<td>100 – 140 kg</td>
<td>40 %</td>
</tr>
</tbody>
</table>

The data and specifications of each type of battery was summarized and tabulated in Table 1. Table 1 displays that the specific energy and energy density of Li-ion type of battery are greater compared to others. This means that the EV powered by the Li-ion batteries was lighter in mass and the batteries pack occupied a relatively small volume space. The Li-ion batteries were already become a very mature technology in powering the EVs for year s[25]. Due to the improved technology of the Li-ion battery, many car manufacturers had implemented the Li-ion batteries into their EV to introduce into the consumer market. Among the well-known vehicles are Nissan Leaf, VW E-Golf, Hyundai Ioniq, Renault Twizzy and Tesla Model S [35].

Currently, the used of Li-ion battery in EV application has developed maturely. It consists a lot of different combination of material for the Li-ion battery and each of the battery has different parameters. A study has also stated that the specific power for the current Li-ion battery can reach approximately 1000 W / kg and can be driven beyond 10,000 W / kg and the energy density of 1000 W / L can be forced above 10,000 W / L when needed, such as motor sports and military applications.
Figure 4 that compares the various type of Li-ion batteries will be illustrated below which consisted of Lithium Titanium Oxide (LTO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Manganese Oxide (LMO), Lithium Cobalt oxide (LiCoO), and Lithium Iron Phosphate (LFP).

As shown from above, NMC, LiFePO4 and LMO has an overall better performance based on the six parameters compared among the six and most of the EVs today were using these three types of Li-ion batteries.

3.2 BATTERY CAPACITY (EFFICIENCY) & TRAVEL DISTANCE

The efficiency of a battery is a function of how much power the battery can charge and eventually discharge which in terms of battery capacity. In fact, different battery models made by different manufacturers had different capacity numbers. In which among of all the batteries types, Li-ion battery technology has been proven that it possessed higher energy density than Pb-Acid battery and other batteries used for EV applications. This means that the same physical space can be used to store more energy in a Li-ion battery. Because with Li-ion batteries, it can retain more electricity as well as able to discharge more fuel, running more devices for long duration at the same time. The travel range of an EV depends on the type and number of batteries used. There are other considerable factors such as terrain, weather or the driver performance but type of batteries being used was the focus. In addition, energy efficiency also related to the battery capacity. The greater the value rated for the battery efficiency, the more percentage the energy stored in the battery can be utilized. Besides, the charging time for a high efficiency battery is faster and allowing the battery can achieve a greater depth of discharge at the same time. Thus, a high efficiency battery corresponding to a battery with a high capacity. Table 2 below has indicated the comparison of the rated capacity from typical batteries used for EV.

<table>
<thead>
<tr>
<th>Type of battery</th>
<th>Energy Efficiency (%)</th>
<th>Nominal Voltage (V)</th>
<th>Rated Capacity (Ah)</th>
<th>Rated Capacity (kWh)</th>
<th>Distance that can travel on a single charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead – Acid</td>
<td>85</td>
<td>6</td>
<td>215</td>
<td>1.29</td>
<td>Approximate 22 miles [36]</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>85</td>
<td>343</td>
<td>77</td>
<td>26.4</td>
<td>75 - 150 miles</td>
</tr>
<tr>
<td>Na-NiCl2</td>
<td>75</td>
<td>278.6</td>
<td>64</td>
<td>17.83</td>
<td>~ 120 miles</td>
</tr>
<tr>
<td>Li-ion</td>
<td>90</td>
<td>350</td>
<td>158</td>
<td>55</td>
<td>250 miles</td>
</tr>
</tbody>
</table>

Some of the batteries from the existing EVs were taken to compare the battery capacity. Lead-acid battery properties was determined from 6 V electric golf car [38], Ni-MH battery properties was determined from General Motors EV1 [39], Na-NiCl2 battery properties was determined from the Z5-278-ML-64 series and Li-ion battery properties was determined from the current Tesla Model 3 - Standard Range Model [40]. From Table 2, it can be clearly seen that the Li-ion based battery has the greatest battery capacity (kWh) compared to others and most of the current EVs are all using Li-ion based batteries. As observed from table above, Li-ion based batteries have the overall greater performance in EV application. Therefore, most
of the current EVs are utilizing Li-ion based batteries to be the power source in propelling the vehicle as Li-ion batteries outperformed others in significant parameters. Some of the aspects that affect the battery capacity would be discussed.

In fact, the battery capacity is affected by several factors such as internal resistance, type of discharging method, discharge mode and rate of discharge and charge. If the battery cannot deliver the stored energy effectively, it will limit the use of battery capacity. Thus, a battery needs a low internal resistance (IR) as it is the person in charge of the amount of the energy that can be delivered. A high resistance will heat up battery and cause a voltage drop under load.

**Table 3.** Relationship between type of battery, internal resistance and impact to battery capacity

<table>
<thead>
<tr>
<th>Type of battery</th>
<th>Internal Resistance</th>
<th>Impact to battery capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead – Acid (VRLA)</td>
<td>15 – 16 mΩ [41]</td>
<td>Low resistance – smooth flow</td>
</tr>
<tr>
<td>Ni – MH</td>
<td>778 mΩ [42]</td>
<td>High resistance restrict flow</td>
</tr>
<tr>
<td>Na – NiCl2</td>
<td>180 mΩ [43]</td>
<td>Relatively low resistance</td>
</tr>
<tr>
<td>Li – ion</td>
<td>320 mΩ [42]</td>
<td>Moderate resistance</td>
</tr>
</tbody>
</table>

Another factor is the different types of discharging mode of the battery. There are basically two types of discharge which are continuous discharging and intermittent discharging. Continuous discharging refers to when battery continuously supply energy to load without rest which the capacity is dropping continuously. Intermittent discharging means connect and disconnect the battery to drive a load at an interval period. Some voltage will be recovery during this period and it will provide a longer discharging time. Three common discharge modes consisted of constant load, constant current, and constant power. Constant power mode has the shortest discharge time, followed by the constant current and then constant load. Lastly, the discharge and charge rate of the battery. Repeating overcharging and over-discharging a battery can reduce the battery capacity as well as its lifespan.

Most of the Nickel-based batteries have suffered from the memory effect problem. Basically, the Nickel-based batteries will retain its memory of the most often used of depth of discharge in the recent past. For any value that exceed the regular usage of DOD, the battery cannot perform well beyond the value, and partly decreases its unused capacity for future use. For instances, as shown in Figure 5, the point M represents the frequent usage of a Ni-MH battery with a 25 % charging and discharging of its capacity, in which the point M will be remembered by battery itself. For any usage beyond point M at the next subsequent use, it will cause battery cell voltage to fall below its original value as indicated by dotted line in the figure below [44]. So, memory effect is one of the reasons that makes Nickel-based batteries are not the ideal type battery for EV purpose.

3.3 SELF-DISCHARGE & CHARGING TIME & TEMPERATURE

This section will be focused on the charging parameters of each types of batteries used for EV. A battery’s charging and discharging rate are subject to C-rates. A battery’s power is usually rated at 1 C, so a fully charged 1 Ah battery should provide 1 A for an hour. Over two hours, the same battery discharge at 0.5 C should provide 0.5 A, and for 30 minutes at 2 C, 2 A. A higher C-rate meaning can provide more current flow in a relatively short time [45].

First and foremost, the Pb-Acid battery. As mentioned at the previous section, Pb-Acid battery consisted of two types which are Starting battery and Deep-Cycle Battery. However, the common lead-acid battery used for EV application was the VRLA which from deep-cycle category while some EVs still using SLI type for auxiliary function. Most of the Pb-Acid batteries has a self-discharge rate of 5 % per month [46]. In fact, all types of batteries suffered from the self-discharge problem. It is a permanent process and cannot be reversed. It is a part of battery characteristics but not a manufacturing defect, but poor fabrication process and improper handling can further worsen the discharge rate per month. Self-discharge in the form of leakage fluid indicated that the highest self-discharge rate occurs immediately after charge and tapers off. Based on research, the Pb-Acid battery and Li-ion battery have a lower self-discharge rate compared to Nickel-based batteries.

Normal Pb-Acid battery has a charging time of around 8 – 16 hours for a deep-cycle charge at a charging temperature around -20 °C to 50 °C [46]. The lead-acid battery is encouraged to be always stored in a charged state (2.10 V) to avoid sulfation [47]. The lead-acid battery is best to operate at an optimum temperature of 25 °C and has high overcharge tolerance. The acceptable operating discharging temperature for the lead – acid range between -45 °C - +50 °C [31]. However, the lead-acid battery has a low charging rate of 0.1 C – 0.05 C which it needs longer duration to full charge the battery itself [48]. The lead-acid battery has a columbic efficiency around 90 % [46]. Coulombic efficiency (CE), also known as faradic efficiency or current output, defines the efficiency of charge that transmit electrons into batteries. CE is the proportion of the battery's
total discharge capacity to the battery's total charge capacity over a full cycle. The longevity of the battery will be reduced as temperature goes higher. According to study, the battery life is cut in half for every 8 °C increase in temperature. A VRLA that would last at 25 °C for 10 years would only be good at 33 °C for 5 years. If maintained at a steady desert temperature of 41 °C [49], the same battery will desist after 2 1/2 years. The nominal cell voltage of Pb-Acid battery is 2 V[46].

For the Nickel-based battery, the typical battery that normally used for EV application is the Ni-MH battery. Most of the Ni-MH batteries have a high self-discharge rate around a value of 20% - 30% per month [46]. Whenever a Ni-MH battery must be used, it needs to be recharged first. It takes around a charging time of 3 hours for rapid charge and an hour for a fast charge purpose [47]. The Ni-MH batteries usually has an optimum range of operating temperature from -30 °C to 65 °C [47]. Unlike lead-acid, Ni-MH battery has a low overcharge tolerance as can damage the battery cells and create potential hazards such as depleted battery capacity, possible explosion and generate excessive heat [50]. It has a peak load current C-rates of 0.5 C – 5 C [46]. The Ni-MH batteries commonly has a columbic efficiency of 70% for slow charge and 90% for fast charge [46]. The nominal cell voltage of Nickel-based batteries is around 1.2 V [46].

For the ZEBRA battery, it has a negligible self-discharge rate or none [37]. The ZEBRA battery has a 100% coulombically efficiency, in which the capacity charging in equal to capacity discharging out [37]. It is because the ZEBRA battery has a chemical element that possessed good electronic insulating properties and has no chemical side reactions, which is the sodium ion conducting beta alumina. In terms of the charging time, ZEBRA battery takes about 6 hours for normal charge and an hour for a fast charge [51]. It has an optimum operating temperature from 270 °C – 350 °C as the beta alumina electrode contribute only a little amount resistance at these temperature [37]. The nominal cell voltage of ZEBRA batteries is around 1.2 V [46].

For the Li-ion based battery, it has a small discharge rate per month with a value less than 5% / month [46]. The Li-ion based batteries normally has a columbic efficiency of 99% and battery remains cool during charge [46]. For the charging time, Li-ion based batteries has a charging duration about 2 – 3 hours for a complete charge[46]. Li-ion batteries manufacturers recommended using a 0.8 C or less to prolong the battery life, nevertheless, most Li-ion batteries can take a higher charge C-rate with only little stress. Thus, The acceptable range of discharging temperature and charging temperature for the Li-ion batteries are ranged between -20 °C – 60 °C and 0 °C - 45 °C respectively and it has a low overcharge tolerance[47]. It has a peak current range from 10 C – 30 C [46]. The Li-ion battery was encouraged to be stored at an intermediate DoD with a value of 3.7 – 3.8 V. It is advised to avoid storing the Li-ion batteries at full charge and above room temperature as irreversible self-discharge will occur [47]. The nominal cell voltage of Li-ion based batteries is around 3.2 V – 3.7 V [46].

Under normal circumstances, Li-ion’s self-discharge is relatively stable throughout its service life; nevertheless, there is a rise in maximum loading status and high temperature. Longevity is also influenced by these same causes. In contrast, a fully charged Li-ion is more likely to fail than a partly charged Li-ion. Table 3 displays Li-ion’s self-discharge at different temperatures and level of charge every month. As shown in the table, the Li-ion battery has a higher self-discharge rate at a high temperature with a full charge. Hence, it can be concluded that the self-discharge rate of the Li-ion battery is directly proportional to the operating temperature and the state-of-charge of the battery itself. It is advisable to not discharge a Li-ion battery below 2.50 V/cell as it will turn off the protection circuit at that state, in which the battery will not able to be charged by most of the battery chargers[52].

Table 4. Relationship between of the various temperature and state-of-charge in affecting the self-discharge rate per month of the Li-ion battery [52]

<table>
<thead>
<tr>
<th>State-of-charge</th>
<th>0°C</th>
<th>25°C</th>
<th>60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full charge</td>
<td>6%</td>
<td>20%</td>
<td>35%</td>
</tr>
<tr>
<td>40-60% charge</td>
<td>2%</td>
<td>4%</td>
<td>15%</td>
</tr>
</tbody>
</table>

3.4 LIFETIME / LIFECYCLE AND COST

In this section, cost, lifespan and lifecycle parameters for the different types of batteries that utilized in EVs will be discussed. The Pb-Acid battery act as the ancestors for all the recent technology of batteries and has the overall lowest cost compared to Ni-MH, ZEBRA as well as the Li-ion battery. Due to low specific energy and energy density value, utilization of Pb-Acid battery in the early EVs is limited. From past until today, the Pb-Acid battery that typically use for EV application is the valve-regulated type (VRLA). VRLA has a fast recharge capability, high specific power and low initial cost as well as having a maintenance-free operation [28]. Nevertheless, it suffers from a low cycle life about 1000 cycles at the depth of discharge (DOD) of 50% and has an initial cost of $120 / kWh[24] as well as having a lifetime of roughly 3-15 years. Depth of discharge is a parameter used to determine the total amount of the discharged battery. In fact, the amount of discharged for a typical lead-acid battery should not exceed 50% as it will shorten the battery life [53]. The dominant reason for its relatively short lifecycle of the VRLA battery. For examples, the grid of the positive electrode corrodes, active material depletes and positive plates expands in the battery [54].

As shown in Figure 6 below, it illustrated that the higher depth of discharge used for a battery, the less life cycle that a battery is. An alternative way to think of loading a battery or discharging it is to visualize it as a balloon. If you constantly inflate a balloon to its maximum capacity and then totally deflate it, repetitive pressure will fatigue the material of the balloon. Imagine now that by inflating repeatedly with another balloon and deflate it from 50% to 90% full, the material will become less stressed and last longer than the first balloon. Likewise, the concept of the balloon example is like the battery technology. The plate inside the battery is exposed to the same pressure as the balloon content. In this example, when
compared to Pb-Acid battery, Li-ion batteries are simply manufactured from a more superior, greater balloon material.

![Figure 6. Number of cycles against DoD for VRLA battery][55]

A higher working temperatures and high discharging current condition would accelerate the aging phenomenon not only for the lead-acid battery but also for others as shown in Figure 7.

![Figure 7. Relationship between battery capacity, discharge rate and operating temperature][56]

After introducing of the nickel-based battery into the EV, the usage of lead-acid battery for the EV has reduced as the nickel-based battery has a higher specific strength and energy density compared to Pb-Acid battery. Among of the nickel-based batteries, Ni-MH was the one commonly used for EV application. It is because that Ni-MH battery has no utilized cadmium material act as the electrode and more environmentally friendly. Ni-MH also has a great specific energy and energy density among other nickel-based batteries. Since after the introduction of Ni-MH battery in 1991, the battery technology has developed rapidly until today. But, mostly Ni-MH batteries are used for Hybrid Electric Vehicle (HEV) application such as Toyota Prius and Honda Civic Hybrid as it has a great specific power value. According to study, a Ni-MH battery has a lifecycle as high as 3000 cycles with the battery operating between 20 % - 80 % DOD. The life requirements of full-function battery EVs and plug-in HEVs could be achieved with a full-function Ni-MH battery[57]. At a DOD of 80 %, the lifecycle of the Ni-MH battery can be achieved over 1000 cycles for current trend. It is believed that lifetime for a Ni-MH battery used for EV can be last over 7 years[58]. The cost for a Ni-MH battery is somewhere around $ 200 – 350 /kWh [59]. In fact, due to roughly one third of the mass of a Ni-MH battery pack was originated from the nickel metal itself and the price of nickel has a large impact on the overall price of a Ni-MH battery pack [60].

After the introduction of the Ni-MH battery into the EV field, there is another alternative battery which come after Ni-MH which was Sodium-Nickel Chloride (Na-NiCl2) or ZEBRA battery. This battery is commonly used for public transportation such as bus or van due to its high operating temperature. Thus, for this battery, it has a lifecycle of around 1000 cycles at 80 % DOD and expected to cost roughly between $160-300 /kWh [28]. Lifetime is expected to be sustained more than 10 years [51]. Overall for the ZEBRA battery, it has a greater performance compared to lead-acid but it is only able to perform its maximum efficiency at temperature around 250 – 350 °C which made this battery only suitable for urban public transportation.

In 21st era of centuries, the most modern battery technology used in EVs is the Li-ion based battery. It is majorly used for many EV application and HEV today such as Nissan Leaf, Toyota Prius, Honda Insight and Tesla Model due to its long cycle life and high energy density. Considering the customer-driving profiles, the Li-ion battery is designated in a way to ensure that it can be performed full-operating capability at least 10 years. According to one of the studies, Li-ion battery was believed that it has reached its end of life when the cell achieved 80 % of beginning of life power or 80 % of beginning of life capacity. The Li-ion battery can be able to provide a total energy of up to 800,000 kWh for a 10-year vehicle life depending on the demand for power and vehicle mileage expectations [61].

Besides, the cost for the Li-ion battery pack is high at the initial stage when the Li-ion was freshly introduced into EV application which having a value of $ 1000 +/kWh in the year around 2005 – 2010 and expected to drop to below $ 400 /kWh in future trend as shown in Figure 8 [62]. However, due to progressively advanced technology in battery field, the process to manufacture the Li-ion battery become simplified as well as a lot of alternative materials can be utilized in the Li-ion battery which has a lower cost. Based on a market analysis paper, the author made a core conclusion that the reduction of the costing to manufacture a full automotive Li-ion battery packs has been reached to roughly $410/kWh industry-wide whereas automotive car manufacturing leaders such as Tesla and Nissan predicted the Li-ion battery cost around $300/kWh [62]. Likewise, the lifecycle of the Li-ion battery also depends on the DOD. The larger the DOD, the shorter the lifecycle for a Li-ion battery and avoid fully discharging and charging the Li-ion battery between uses to prolong the battery life. One more thing is that Li-ion battery has no memory effect and does not required periodic full discharge cycles to extend life. A typical type of Li-ion battery that used for EV application is Nickel Manganese Cobalt Oxide (NMC) such as Nissan Leaf, Chevy Volt and BMW i3 [18].
The discharge cycle for the NMC battery at each of the DOD will be shown in the Table 5 below. A typical Li-ion based battery can have a lifecycle around 500 – 2000 cycles at a 80% DOD condition [46].

Table 5. Lifecycle for Li-ion (NMC) battery at different DOD Level

<table>
<thead>
<tr>
<th>Depth of discharge (DOD)</th>
<th>Discharge Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 % DOD</td>
<td>~ 300</td>
</tr>
<tr>
<td>80 % DOD</td>
<td>~ 400</td>
</tr>
<tr>
<td>60 % DOD</td>
<td>~ 600</td>
</tr>
<tr>
<td>40 % DOD</td>
<td>~ 1000</td>
</tr>
<tr>
<td>20 % DOD</td>
<td>~ 2000</td>
</tr>
<tr>
<td>10 % DOD</td>
<td>~ 6000</td>
</tr>
</tbody>
</table>

According to some of the papers, some estimations has made on the analysis of the battery cost. At year of 2020-2022, the battery pack costs is believed will be reduced to $130–$160/kWh, and at year of 2025, the battery cost is claimed to reach to a price of $120–$135/kWh. Furthermore, Tesla also made a report that the price of the battery cost will become $100/kWh by 2022 due to its NCA-based battery pack design combining with the high-production volume can promote the cost of battery pack become lower. In Berckmans’s finding, by replacing the 2018-dominant graphite with the silicon alloy in the NMC cathode batteries, the battery costs can has a great decrease and solving the cycle-life issues at the same time [63]. BNEF's market survey indicated that the battery pack's volume-weighted average cost is $176/kWh and expects pack-level prices will fall to $62/kWh by 2030 [64].

Figure 8. Cost for Li-ion and future prediction
4.0 BATTERY PACK DESIGN AND CELL DESIGN

4.1 REVOLUTION OF THE DESIGN (FROM INITIAL ARCHITECTURE GEOMETRY UNTIL LATEST DESIGN)

Battery pack is the essential component to power electric vehicles. It is the entire battery energy storage system. It consists of the battery modules, battery management system (BMS) and cooling system. The amount of power needed for EV is huge and hence it needs dozens to thousands of batteries. Current Li-Ion batteries have overheating issues, they are also prone to failure which is caused by mechanical vibration and impact force. The battery pack provides protection to the batteries and manage batteries efficiently and safely. The battery pack design has undergone significant development in recent years.

In 1998, Ford produced the Ford Ranger EV. The first Ford Ranger EV is powered by Delphi lead acid battery. It had 39 battery modules. In 1999, nickel metal hydride version of Ford Ranger was produced. It had 25 Panasonic battery modules. The NiMH Ranger has better performance than lead-acid Ranger. The driving range for lead-acid Ranger is 105 km while the NiMH Ranger has 132 km driving range. The recharging duration also decreases from 8 hours 51 minutes to 8 hours 13 minutes. The mass of the packs has also been reduced significantly from 870.1 kg to 485 kg [65]. The lead-acid Ranger had double layer of modules while the NiMH Ranger had single layer. Figure 10 shows the battery pack of NiMH Ranger.

Figure 10. Battery Pack of NiMH Ranger [65]

Nissan Leaf is an electric vehicle launched in 2010. The battery pack of Nissan Leaf has 48 serially connected modules. Each module consists of 4 battery cells. There are total of 192 battery cells. It uses Lithium Manganese Oxide laminated pouch cell [66]. Laminated cell is smaller than cylindrical cell and thus the packaging can be more compact and flexible. Figure 11 shows the laminated cell used by Leaf.

Figure 11. Laminated Cell [66]
The way of cells connecting in the module is two cells connected in parallel and two cells connected in series. **Figure 12** shows the battery module used by Nissan Leaf.

![Figure 12. Battery Module of Nissan Leaf [66]](image)

The modules are connected in series, and together with the Battery Management System, service disconnect switch and junction box, it forms the battery pack. **Figure 13** shows the battery pack of Nissan Leaf.

![Figure 13. Battery Pack of Nissan Leaf [66]](image)

The battery pack has total energy of 24 kWh. The driving range is 160 km. Comparing to NiMH Ranger, the driving range of Nissan Leaf has increased by approximately 20%.

Chevrolet Bolt EV started to produce in 2017. The battery pack consists of 10 modules, there are eight modules which have 10 groups of cells each, another two modules have 8 groups of cells each. Each group has three cells connected in parallel. There are total of 96 cell groups and 288 lithium ion cells [67]. **Figure 14** shows the battery pack of Chevrolet Bolt EV.

![Figure 14. Battery Pack of Chevrolet Bolt [67]](image)

The cell used is also laminated pouch cell. The group of three cells resembles a book and each group is stacked together which forms the module like a bookshelf. The battery pack has 60 kWh energy, Chevrolet Bolt EV has driving range of 380 km [68], which doubled the driving range of Nissan Leaf. By comparing battery pack of these models, battery pack design has developed in implementing more battery cells in a compact design, storing more energy and increases the driving range.

### 4.2 CELL CHEMISTRY, MATERIALS, BALANCING, INTEGRITY

Batteries provide power to electric vehicle through electricity. The electricity comes from the electrochemical reactions occurred, which results in the flow of electrons and produces electricity [69]. Different types of batteries contain different chemical components and thus the chemical reaction also varies from each other. The theory of the chemical reaction of different batteries is similar.

As mentioned earlier, there are different materials used for the anode, cathode and electrolyte of Lithium-Ion battery. The Lithium battery developed by Sony in 1991 used Lithium Cobalt Oxide (LiCoO$_2$) as the positive electrode and graphite as the negative electrode [70]. During discharge, oxidation is occurred at the negative electrode. The lithium ion and electron are released. The lithium ion moves through the electrolyte while the electrons move through external circuit and both particles react with cobalt dioxide at the cathode to form lithium cobalt oxide. The reaction is in reverse direction when the cell is charging. The electrolyte consists of lithium hexafluorophosphate (LiPF$_6$) and organic solvent.

It was found by researchers from University of Texas in 1996 that the material for positive electrode of Li-ion battery could be phosphate material too[17]. Lithium Iron Phosphate (LiFePO$_4$) battery has longer cycle life than other lithium ion batteries. The negative electrode is also graphite. The half reaction of negative electrode is the same as Lithium Cobalt Oxide battery since graphite is used for both cases. At the positive electrode, Lithium Cobalt Oxide is replaced by Lithium Iron Phosphate [71].

### 4.3 BATTERY MANAGEMENT SYSTEM (REQUIREMENTS, DESIGN, TOPOLOGY)

Battery Management System is an important electronic system to maintain the performance of batteries. Overcharging may damage the batteries. BMS helps to keep the batteries working under safe conditions by monitoring the charging voltage and stops charging when the required voltage has reached [72]. BMS also measures state of charge (SOC), which is the available capacity of batteries [73]. The longevity of battery life is also maintained by BMS.

#### 4.3.1 Requirements for Lithium Ion batteries

Lithium Ion batteries are common batteries used by EV today due to their high energy density and efficiency. However, there is risk of electric shock and fire hazard if not handled properly. BMS is a complex system. There are certain requirements of BMS that have to be met for it to perform all the important task.
4.3.2 Temperature Sensing

The temperature of batteries affects the performance greatly. The range of operating temperature for Li-Ion batteries is -20 °C to 60 °C. Nagasubramanian has found that when the temperature is 25 °C, the energy density of Panasonic 18650 Li-Ion battery was 100 Wh/L and was reduced to 5 Wh/L at -40 °C [74]. Thus, it is important to measure the temperature of batteries. A few temperature sensors are needed and the location where the sensors are placed need to be determined. Simulations can be conducted to find the suitable placements for the sensors. Example of the sensors are thermocouple and fiber sensors [75].

4.3.3 Voltage Sensing

Minimum of one voltage acquisition channel is needed per cell. Most electric vehicles have an additional programmable device which alert BMS whenever any cell is not operated within the allowed voltage range. The voltage acquisition is also responsible for the SOC estimation. If the voltage measured is more accurate, the SOC estimation is better [76].

4.3.4 Current Sensing

The determination of SOC using voltage measurement is suitable during stand-still periods, another method which is suitable for determining dynamic SOC is by measuring current, also known as coulomb counting. The coulomb counter can track the SOC. Current sensors in EV should be capable of measuring current ranging from milliampere to 1000 Ampere [76].

4.3.5 Communication

BMS needs to communicate with other system such as power electronics, energy management system and others, to transmit important information and receive instructions. The common mean of communication is Controller Area Network (CAN). It can provide robust communication under harsh operating environment such as loud electrical noise. Other requirements include electromagnetic interference (EMI) filtering device which reduce the influence of EMI on sensors, galvanic isolation to isolate high voltage part and low voltage part of battery packs, and contactors which can cut off DC currents when hazardous events happen.

4.3.6 Topologies and Design

As mentioned, battery pack consists of many batteries. The Integrated Circuit (IC) of BMS plays important role in monitoring these batteries at once. The front-end IC of modules is referred as BMS Slaves. Their function is acquiring signal and filtering. Another important component is The Electronic Control Unit (ECU), also known as BMS Master. It controls and oversees the electrical system.

4.3.7 The traction batteries of three EV models

4.3.7.1 Mitsubishi i-MiEV

Battery pack of Mitsubishi i-MiEV has 12 modules. 10 modules contain eight cells each and another two modules have four cells each, there are total of 88 prismatic cells [76]. There is a Printed Circuit Board (PCB) mounted on each module, which contains a battery monitoring IC. It can monitor 12 series connected lithium ion cells. There are also three temperature sensors in each PCB. Other components in the battery pack includes contactors, service plug, current transducer, fuses and a fan. The BMS Master is placed under the rear bench seat. The Cell Management Unit (CMU) is connected to BMS Master by Controller Area Network. Figure 15 shows the battery pack of Mitsubishi i-MiEV.

Figure 15. Battery Pack of Mitsubishi i-MiEV [76]

4.3.7.2 Volkswagen e-Up

The battery pack of VW e-Up contains 17 modules connected in series, each module has six pairs of two prismatic cell. There are total of 204 cells in the pack. There are BMS slave in the white box which is situated at the left side of the pack. The fuse, contactors and current measurement is situated below the black cover in the middle. The BMS master can be found in another white box. There is no cooling system in this pack. Figure 16 shows the battery pack of VW e-Up.

Figure 16. Battery Pack of Volkswagen e-Up [76]

4.3.7.3 Smart Fortwo Electric Drive
There are 90 pouch bag lithium ion cells in the battery pack of third generation Smart ED. The batteries are connected in series. There are three PCBs in the battery pack and each of them has six monitoring IC[76]. The BMS master is placed beside the communication signal connector. The fuse and contactor can be found beside the power connector. The entire BMS of Smart ED is placed in the battery case. The space of battery pack is used efficiently and there aren’t many cables used. **Figure 17** shows the battery pack of Smart ED.

![Figure 17. Battery Pack of Smart Fortwo Electric Drive [76]](image)

The main difference between the BMS of these three batteries packs is integration. The battery of Smart ED showed large scale of integration, while there is average amount of integration in the batteries of VW e-Up and Mitsubishi i-MiEV. For Smart ED, the monitoring IC and PCB are mounted on the battery modules in a space saving method. The BMS master is placed inside the pack too. As for the i-MiEV, the BMS master is not placed in the pack, which leads to more cabling required. Smart ED showed large scale of integration, while there is average amount of integration in the batteries of VW e-Up and Mitsubishi i-MiEV. For Smart ED, the monitoring IC and PCB are mounted on the battery modules in a space saving method. The BMS master is placed inside the pack too. As for the i-MiEV, the BMS master is not placed in the pack, which leads to more cabling required.

### 4.4 BATTERY THERMAL MANAGEMENT SYSTEM (BTMS)

Battery temperature affects the performance, reliability and safety of EV. It is important for batteries to maintain within ideal operating temperature range. The four important functions of BTMS are cooling by removing heat, heating to increase temperature of battery when temperature is too low, insulating to reduce sudden change in battery temperature and ventilation to expel hazardous gas from battery [77].

BTMS can be classified into two categories, which are BTMS with vapor compression cycle (VCC) and without VCC. The options of system for BTMS with VCC includes cabin air cooling, direct refrigerant two phase cooling and secondary loop liquid cooling. As for BTMS without VCC, there are phase change material cooling, heat pipe cooling and thermoelectric element cooling.

Production of BMW i3 started in 2013. It uses direct refrigerant two-phase cooling system [78]. The refrigerant evaporator which is implemented in the cooling plate is used to cool the battery. There is phase changing during heat transfer, which helps to keep the temperature almost constant. Audi e-tron started production in 2018. It uses liquid cooling system. There is 22 liters of coolant flowing around the 40 m cooling pipes [79]. Important components such as the electric motor, batteries, stators are liquid cooled. A heat pump is used to utilize the waste heat from the electric motor for heating and air conditioning the interior.

### 5.0 ENVIRONMENTAL ISSUES OF BATTERIES

Batteries can help on replacing our reliance fossil fuels which can make the economy to by greener, although it may make the world greener, the environment footprint for batteries need to be consider too. In this part, lithium-ion batteries will be mentioned regarding the environmental issues since lithium-ion batteries are the batteries that commonly used in these days [80]. Lifecycle analysis (LCA) will be used in this section to calculate the footprint of the environment across the range of impacts on GHG emissions, pollution issues, and more. LCA can be defined as a way of assessing the impact on the environment through the life cycle and process of the raw materials, manufacturing, use, recycling and final disposal of the product [81].

#### 5.1 MATERIAL ISSUE

There are a lot of choices of materials can be used to produce electrodes and electrolytes. Since there are a lot of materials choices, this brings in slot issues such as toxicity, safety, recycling or disposal impacts [82].

##### 5.1.1 Resource Availability

Due to the soaring demand and huge size of future energy storage installations, more material resources need to produce more batteries to fulfill these circumstances [83]. Nowadays, there are enough batteries key constituents, but as the production getting larger years by years, the reserve key constituents for batteries will ended up used up and one day this will be the issue if there aren’t any further action taken when there are still resources in the world [83].

In lithium-ion batteries, the key constituents of this battery are lithium, manganese, cobalt, nickel and natural graphite, it were expected to meet the near-term demand of batteries and the inventor and researcher mentioned that these key constituents are able to supply until the next decades with the rise in demand [83].

In the statement from the researcher and inventor of the lithium-ion batteries does not include the sharp increase in demand where this will boost the market prices. It seems like the amount of lithium left will not be enough to supply for the world to have 100% electrification vehicles [80]. This might happen in the next decades since the production and manufacturing line of vehicles has slowly innovate electric vehicles. It has already been 10% of the world vehicles were functioning with the help of electricity with reducing of fuels [83].
The key constituents of lithium-ion batteries were very limited nowadays in the sense that the minded area were very small selections and this will be very risky in the terms of only supply lithium-ion batteries to the technologies [84].

5.1.2 Environmental Impacts

5.1.2.1 Electrode Materials

Among all the life cycle stages, mineral extraction and metal refining has the most important contributions. Lithium-ion batteries key constituents such as nickel and cobalt will significantly increase the environmental footprint. According the lifecycle analysis, these materials were considered as toxic substances and from the min tailing, this will have the chance of leaking [85]. Besides that, when smelting takes place for the virgin cobalt and nickel recovery, high levels of Sulphur oxide will be produced [86]. Cobalt and nickel can only be mined in a less strict countries on environmental, health and regulations. However, just minimize the leakage will reduce the toxicity where it will benefit the environment, and this will beneficial the environmental performance of batteries [87].

The way to reduce the impact of extractive activities are to increase the efficiency of the resources and recycling or reusing the batteries. Lead acid batteries can be last until this decade are because there are more recycled (secondary) than raw (primary) lead acid batteries were used in worldwide. However, there are new inventor trying to replace lead acid batteries are mainly because the European Chemicals Agency (ECHA) has added lead acid batteries as the Candidate List of Substances of Very High Concern (SVHCs), this is mainly due to the toxic substances [80].

5.1.2.2 Electrolyte Risks

The electrolyte used for batteries brings major impact on the performance of a battery. However, electrolyte performance and safety will need to be compromise. Minor electrolytes substances will bring impact to human health such as the electrolyte of lead acid batteries, sulphuric acid [88]. Not just lead acid batteries, for one of the latest technologies batteries, lithium-ion batteries, it is consider as relatively high flammable and the electrolyte of the lithium-ion batteries will form a toxic atmosphere when the lithium-ion batteries are not closed or semi-closed properly and this aloe the formation of hydrogen fluoride (HF), where it is an extremely toxic and corrosive chemical reaction. This will only occur when there are car crashing happening or any incident that not closing the batteries properly [88].

5.1.2.3 Binders

Binders is like a glued where is “glued” the components of the battery together. The binders used has cause impact to the environmental. Majority binders are made of fluorinated substances, this is because these substances will produce energy intensive and the emission of ozone depleting substances [87]. In the terms of recycling, it needs further process such as toxic solvent to break down the binders only can be recycled, and it is not biodegradable[89]. Therefore, the binders took another process, but it can still be considered as a substance that can be recycled.

5.2 ENERGY ISSUE: PRODUCTION & CHARGING

5.2.1 Energy Source for Production

The carbon intensity normally used in producing batteries have a big impact on the environment footprint. In the production of lithium-ion batteries, the production can be very complicated, this is because to prevent the HF to be formed therefore it need to be manufacture at extremely low humidity and cell assembly at very dry surroundings [90]. According to a research paper stated that there are 7 types of lithium-ion batteries which assessed cumulative demand of 19 studies and took the average of 1 Wh of lithium-ion batteries needs approximately 328Wh of energy to produced. With the 1 Wh will be around 110 grams of CO\textsubscript{2}, which are the GHG emissions[90]. Asian country is mostly placing to manufacture lithium-ion batteries with some mixture of electricity which results differently compared to majority of the Europe countries [91]. An example shows that in South Korea, the lithium-ion batteries there are production with the mixture of coal, nuclear and gas. This results that the impact to the global warming will be 60% higher than using 100% electricity supply [91].

After all these incidents, the things that can overcome GHG emissions from the production of batteries will be by making sure that the cells can be fully renewable sources [92]. When the world thinks that this is nearly impossible, but there goes in one of the largest batteries’ factory in Sweden, in the year of 2023, the manufacturing batteries factory will make sure it will be 100% powered by renewable sources such as hydropower [92].

5.2.2 Roundtrip Efficiency

Roundtrip efficiency can be defined as a place to store the energy and give the energy back to the grid. In mathematically term it means the ratio of energy input is the ratio of energy output which it is normally calculated in percentage. It can be simplified with saying that when the power needs to be used, the amount of energy coming out when there is discharge occurring of a secondary (recycled) battery.

In a commonly used lead acid battery, there are efficiency over 70-80%. In another words, 20-30% of the energy will be lost during the charging cycles. In another hand, lithium-ion efficiency is over 90%, where after the charging cycle, only 10% of the energy will loss. All these lost energies will be the impact to environmental [87]. It is a serious scenario since if the improvement to overcome these issues can be reduce from 90% to 92% for lithium-ion battery, these 2 % difference will lead to 7% reduction from the impact of environmental [93].

5.3 LIFESPAN

If a battery has a longer lifespan, it drags the number of times on replacing the battery. The longer the lifespan will also affect the cost reduced by relating it back to less impact to the
environment. In real life application, battery in the electronic vehicle’s lifespan is longer than the other smaller electronic device. If the battery drained up dramatically, users will change the whole electronics away and this will consider as end-of-life (EoL) of the whole electronics which will increase the impact of environment.

Battery’s lifespan has 2 categories to differentiate the batteries namely calendar years and life cycle. For calendar years, the inventor will calculate the maximum use of the batteries with the length of time. For example, the battery can last for 3 years, then the battery will be drained off completely. On the other hand, life cycle of the batteries is where the inventor will calculate with the number of charges to the batteries. For example, if the battery can be charge for 2400 cycles, after 2400 cycles, the battery will be “half dead” or completely not functionable. For the case of using lead acid batteries, it will go through 3 phases which are formatting, peak and decline [94].

![Figure 18. The three phases of lead acid batteries [94]](image)

From Figure 18, it clearly shows how a battery life span will be like. In formatting, this required 20-50 cycles to reach the second phase, which is the peak phase. It will take 100-200 cycles to reach the third phase which is the decline phase. To increase the lifespan of lead acid batteries, these batteries must make sure to charge for ± 15 hours [94]. For lithium-ion batteries, the peak it can reached 2000 cycles, in another words, the lead acid batteries result higher impact on environmental compared to lithium-ion batteries.

### 5.4 END OF LIFE (EOL)

Recycle and reuse can be the ways for batteries that came end of life (EoL). Recycle in batteries also called as secondary batteries, this will give a big hand on reducing impact on environmental Besides that, by comparing on increasing the lifespan, reuse the batteries will be a better choice [80].

#### 5.4.1 Recycling

Recycling has the direct environmental benefits. In lithium-ion batteries, if the cathode used were materials such as aluminum and copper, this may help the environment to save over 50% of its lifetime which is a decade’s number [80]. As mentioned earlier in section 5.1.2, the reduction of sulphuric oxide will be emission by approximately 100% which is emission completely since it prevents from smelting [86]. Somehow it will be challenging to recycle lithium-ion batteries [95]. It contains a huge number of mixed materials in lithium-ion batteries, where compared to simpler batteries such as Pb-Acid batteries, the lithium-ion battery is much more complicated. For an electric vehicle that powered by Li-ion battery, at least 100 individual cells are needed [95]. Some of the materials need to be separated in the lithium-ion batteries as the composition of the materials is not allowed to be recycled.

When there are lithium-ion batteries without any labeled on it, it stand for there are some of the compositions are not allowed to be recycled [95]. Due to the production of electric vehicles, the number of productions for lithium-ion batteries reaches approximately 25 billion by just 2019 globally [96]. The method of extracting cobalt, nickel and copper were known one of the most economically valuable resources in the field of recycling lithium-ion batteries, the other products will not be recycled and neglected as there are too many cells in lithium-ion batteries [95]. The main reason that cobalt lithium-ion batteries can be recycled is that cobalt is a precious element, so if cobalt is not extracted, the recovery of lithium-ion batteries will be commercially unattractive [96].

#### 5.4.2 Reuse

Batteries from electric vehicles that has lost the initial capacities can be used in other lesser demand energy storage, it means by lost the initial capacities means the batteries has only 75% compared to the initial capacities [89]. In some of the research studies stated that secondary lithium-ion batteries are feasibility and environmental benefits [97]. There are some challenges to reuse due to the complex physical and chemical process, one of the challenges is to design a battery management system which fulfill the qualification of evolution [98].

### 6.0 CONCLUSION AND FUTURE DEVELOPMENT

The development and revolution of battery technology from old centuries to latest battery technology have been reviewed in the paper. The revolution processes and parameters of the rechargeable batteries from the earliest which is Pb-Acid battery to the recent latest Li-ion battery were examined. Based on the evolution from lead acid battery to lithium ion battery, the parameters such as specific energy, energy density, specific power, weight and size had enhanced along the evolution. The battery specific energy, energy density and specific power have increased over the evolution and the weight and size of battery have significantly decreased over the years. Tin terms of battery capacity and travel distance, the lithium ion battery has the best performance among the other batteries. The charging time and the discharge time of the batteries were also discussed. The lifetime / lifecycle and cost of the evolution of batteries were also reviewed. However, there are currently a few developing batteries which use different anode, cathode and electrolyte separator that could possibly enhance the performance of the batteries by increasing the parameters such as heat capacity, lifetime / lifecycle sustainability. The...
revolution in terms of the essential of battery pack design and cell design were considered in the review paper. This include the cell chemistry, materials, balancing and integrity of batteries. The attributes of battery management system, thermal management system for battery pack and the battery state estimation were deliberated. Lastly, the sustainability issues of the batteries including the impact of batteries to the environment, the degradation/aging defects, the recyclability, repurposing and extend life issues were discussed in detail.

Li-ion batteries have changed dramatically over the past 25 years, making it possible to introduce better performance in consumer electronics and new applications such as drones and EVs. Nonetheless, innovation is crucial to speed up these and other implementations—a step-change in efficiency is required. There’s a lot going on in innovations of the next century. A host of battery technologies are being built by innovative start-ups utilizing new materials, while in the Li-ion sector there is growing development focusing primarily on three areas: silica anodes, advanced cathodes and solid-state electrolytes. The silica anodes technology will be used to replace the carbon or graphite anode in Li-ion batteries. The Li-ion anode substitution with silica anode technology will increase the battery capacity in absorbing ions because each silicon atom will take up to four lithium ions, whereas six carbon atoms absorb just one lithium in graphite anodes. It is therefore stated that it can improve the energy density up to 40%. However, to implement this technology in current Li-ion batteries, cycle-life issues need to be addressed as the silicon atom will expand up to 300 percent volume while charging, which can cause it to break and cause the battery to fail. Ongoing technologies use only small concentrations of silica which restrict possible increases in density to 10–20%.

One of the future developments of the battery system industries that can contribute to the progress of battery for electric vehicles is the investment of magnesium-ion batteries. Rechargeable magnesium battery (RMB) is potentially contributing more to the automobiles industry after Lithium-ion battery due to its relatively safe characteristic regardless of it being a reactive metal, the high specific capacity and richness in the earth’s crust. The availability and cost of magnesium is winning over its counterpart which is the lithium-ion battery.

Another potential battery that possibly could be developed further to achieve equally if not more of what lithium ion battery has achieved is the sodium ion battery (SIB). The positive aspects of sodium ion battery including the richness of sodium precursor materials in the earth as well as its low budget. Lithium precursors are about 25–30 times more expensive than the sodium precursors. Due to the expansion of knowledge of developing lithium ion over the decades, the theories that have been accumulated during the research and development of lithium ion battery can be used in developing the sodium ion battery.

However, the current limitations of sodium ion battery include the identification of suitable materials to have layered materials which have been adopted by the lithium ion battery for most applications. Comparing to lithium ion battery, the sodium ion battery has lower energy density because of the layered sodium ion battery cathode materials has operating voltages of up to 1.5 V lower than lithium ion battery’s layered. The success of further research, investigation and development on the materials to have layered materials that is suitable to use on the sodium ion battery system will let sodium ion battery to make a major impact on the electrochemistry industry.

Ultimately, in EV applications, the battery plays the most important core role. To encourage more industrial EV implementations in the future, other battery targets such as long lifecycles, high specific energy and power, and the right amount of price that can compare with an ICE must be met.


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