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An Analysis of Electrical Vehicles' Batteries

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***Abstract*: The advent of electrical vehicles has revolutionized transportation. The gases produced by the conventional vehicles powered by fuels such as diesel and petroleum, and a potential shortage of these fuels led to the interest in electric vehicles. The electrical vehicles on the other hand are powered by lithium-ion batteries and offer a possible solution to the increasing pollution as they only emit natural by products instead of exhaust fumes and harmful gases like carbon monoxide, nitrogen oxides, hydrocarbons from unburnt fuel and particulate matter such as soot. A very interesting component of an electrical vehicle is its battery. The batteries of most electrical vehicles are made of lithium-ion and are the reason why electrical vehicles are so distinguished from their conventional fuel powered counterparts. The paper focuses on the various batteries that have been used over the course of the years in different electrical vehicles. It talks about the history of battery performance improvement and includes descriptions of the following types of batteries: Lead-acid batteries (Pb-PbO$_2$), Nickel-Cadmium Batteries (Ni-Cd), Nickel metal Hydride batteries (Ni-MH), Sodium-Nickel chloride batteries (Na-NiCl$_2$), Sodium sulfur batteries (Na-S) and Lithium-ion batteries. The lithium-ion batteries have been discussed in detail due to their relevance in today's electrical vehicles. However, there is also a discussion of solid-state batteries and their features because of their superiority over lithium-ion batteries and how they can be the next major choice for electrical vehicles' batteries soon. It also describes the various batteries' indices and characteristics such as power density, energy density, specific energy, battery capacity, internal resistance, working temperature and efficiency. The conclusion of the paper mainly focuses on the future of electrical vehicles, their batteries, and their impact on the environment in the long run. The paper also discusses the few hurdles that electrical vehicles face today due to which many nations haven't been able to switch from conventional vehicles to electrical vehicles yet.**

***Keywords*: electrical vehicles, batteries, battery performance, specific energy, energy density.**

1. Introduction

Modern cities required an alternative mode of transportation due to the increased pollution and severe environmental problems caused by an increased use of transportation. A gradual switch to green technology thus became inevitable. The first successful small-scale electrical vehicle debuted in 1890 in Iowa. It was created by chemist William Morrison. In about 1899 these vehicles started gaining popularity. Unlike their steam and gas-powered counterparts, they were much quieter and easier to drive. Moreover, they did not emit any pollutants. By 1901, the world's first electrical hybrid car was invented by Ferdinand Porsche. A gas engine and electricity stored in a battery provided power to the vehicle. However, by the 1920s, better roads and cheaper prices of crude oil contributed to the decline of these vehicles. In the span of 30 years, the cheap and abundant gasoline prices ensured that the prices of these fuels would soar through the roof. Thus, in the 1960s and 1970s, interest in electrical vehicles rose again. But due to their limited range and performance, electrical vehicles could not be implemented easily. Soon enough, in the 1990s, due to renewed government guidelines, General Motors manufactured the EV1, which gained huge success among the masses. Following the EV1's success, Toyota introduced the first mass produced hybrid- the Prius. In 2006, Tesla Motors in the Silicon Valley announced their luxury electric sports car with a range of more than 200 miles. Other automakers took note of this, and this led to several improvements in the manufacture and features of electrical vehicles.

The advent of electrical vehicles has revolutionized transportation. The gases produced by the conventional vehicles powered by fuels such as diesel and petroleum, and a potential shortage of these fuels led to the interest in electric vehicles. The electrical vehicles on the other hand are powered by lithium-ion batteries and offer a possible solution to the increasing pollution as they only emit natural by products instead of exhaust fumes and harmful gases like carbon monoxide, nitrogen oxides, hydrocarbons from unburnt fuel and particulate matter such as soot. A very interesting component of an electrical vehicle is its battery. The batteries of most electrical vehicles are made of lithium-ion and are the reason why electrical vehicles are so distinguished from their conventional fuel powered counterparts. We turn to some of the interesting features of these batteries next such as the batteries' indices, characteristics, comparison of the different types of batteries and the future of the batteries of electrical vehicles.

A. Theory

An integral part of any electrical vehicle is its battery, the source of power for the EV. The types of batteries that have been used over the years have changed with time. Prior to the 1990s, secondary batteries were primarily either lead- acid batteries or nickel-cadmium (NiCad) batteries. The energy density of the NiCad batteries was at most 50 Wh/kg which was a huge disadvantage. Following these batteries, in the early 1990s, nickel-metal hydride batteries were introduced.

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Following these batteries, several other types of secondary batteries were introduced before the modern lithium-ion batteries came into use. Major EV companies such as Tesla currently use NCA batteries which stands for Lithium- Nickel-Cobalt- Aluminum batteries. Lithium- Nickel- Manganese-Cobalt batteries are also quite common in the EV industry presently.

2. History of Battery Performance Improvement

Lead-acid batteries (Pb-PbO_2): They are the oldest kind of rechargeable batteries. Invented in 1859, these batteries were commonly used in conventional vehicles and have also been used in electrical vehicles. These batteries are formed by a sulphuric acid deposit and a group of lead plates. The anode is made up of lead sheets packed with spongy lead, while the cathode is made of lead grids packed with PbO_2. Sulphuric Acid of about 38% strength (%w/w) is used as the electrolyte. The anode and cathode are alternatively arranged in the electrolyte and are separately interconnected. During the loading phase, PbSO4 is reduced to Pb at the cathode and PbO_2 is formed at the anode. They have a very low specific energy of about 35-40 Wh/kg and a low energy density of about 80-90Wh/L. The GM EV1 and the Toyota RAV4 EV use Lead acid batteries.

Nickel-Cadmium Batteries (Ni-Cd): They were primarily used in the 1990s. They consist of a cadmium electrode in contact with an alkali and acts as an anode while NiO2 in contact with an alkali act as the cathode. The alkali used is a moist paste of potassium hydroxide. These batteries have a cell potential of about 1.4 V, specific energy of 40-60 Wh/kg and energy density of 50-150 Wh/L. The downside to them is that they present high memory effects, have a low lifespan and cadmium is a pollutant.

Nickel metal Hydride batteries (Ni-MH): In these batteries, the anodes are made of hydrogen absorbing alloys and the cathodes are made of Ni $(OH)_2$. The electrolyte is an alkaline solution of KOH. They are of the same size as Ni-Cd batteries, but they have significantly more capacity and energy density than the Ni-Cd batteries. Electric vehicles such as the Toyota Prius and the second version of the GM EV1 made use of such batteries. In 2014, about 95% of the HEVs used nickel metal Hydride batteries.

Sodium-Nickel chloride batteries (Na-$NiCl_2$): In these batteries the cathode is made of $NiCl_2$, and the anode is made of Na. The electrolyte, NaAlCl4(tetra chloroaluminate of sodium), is in its liquid state at the operating temperature of around 270- 350 degrees Celsius. These batteries have a high energy density of about 95-120 Wh/kg and have extremely long-life cycles. They have been commercialized since the mid-1990s and have been used in various HEVs and EVs.

Sodium sulfur batteries (Na-S), which contain sodium liquid (Na) and sulfur (S): This type of battery has a high energy density, high loading and unloading efficiency (89–92%), and a long-life cycle. The materials used in these batteries are economical too. This type of battery is used in the Ford Ecostar, the model that was launched in 1992–1993.

Lithium-ion batteries: The most used batteries in electric vehicles at present are lithium-ion batteries. They contain an anode, a cathode, an electrolyte, and a separator. These batteries use a lithium salt as an electrolyte, which carry the positive lithium ions from the anode to the cathode via the separator. They are light, have high loading and unloading cycles, have high loading capacities and present a reduced memory effect. They have a specific energy of about 100-275 Wh/kg and an energy density of 250-693Wh/L.

The diffusion equation of the lithium ions in the active material is given by,

$$\frac{\partial C_s}{\partial t} = D_s \nabla_r^{\,2} \cdot C_s \tag{1}$$

The notation is as follows:
C: Concentration of lithium ions.
D: Diffusion coefficient of lithium ion.
∇: Del Operator.
r: Radial distance in a particle of active material.
‘s’ represents that the material is in an active state.

The equation for the lithium-ion transport in electrolyte is given by,

$$\varepsilon \frac{\partial C_e}{\partial t} = \varepsilon D_e \nabla_X^{\,2} \cdot C_e + \frac{(1-t_+)}{F} a i_n \tag{2}$$

The notation is as follows:
ε: Porosity
X: Distance from the negative electrode current collector.
t_+: Transference number of cations.
F: Faraday’s constant.
A: Surface rate of active material.
i_n: Current density.

Even though lithium-ion batteries are most used today due to their superiority, another type of batteries that seems to be promising is the solid-state batteries. The differences between these batteries and solid-state batteries are Lithium-ion batteries are made up of a cathode, anode, separator and liquid electrolyte and use the electrolyte to regulate the lithium ions. The solid-state battery provides up to 2.5 times the energy density compared to the lithium-ion battery. It has a longer lifespan. It is smaller and more lightweight. And because of its size, it is safer too. All EVs could benefit from these batteries as it will be much lighter than their lithium-ion counterparts. They recharge 4-6 times faster and offer much more rage too. Lithium-ion batteries are subject to thermal runaway- a chain reaction caused within a battery that is very difficult to stop and occurs when the battery reaches a temperature where a chemical reaction is caused inside the battery. Thus, they can be very explosive. Solid batteries on the other hand are nonflammable and thus present a much lower risk of igniting a fire.

We have talked about the history of the different batteries used and gone in depth into the working of the lithium-ion batteries and a comparison between these types of batteries and the solid-state batteries. We now turn towards the general characteristics of any battery used in an EV.

Table 1
Examples of electrical vehicles which run on Li-Ion batteries along with their capacities, power, and price

Model Name	Battery type	Capacity	Power	Price
Renault Twizy	Li-Ion Battery	6.1 kW/h	4 kW	6,750 €
Hyundai Ioniq	Li-Ion Battery	28 kW/h	88 kW	29,500 €
Nissan Leaf	Li-Ion Battery	30 kW/h	80 kW	30,680 €
VW E-Golf	Li-Ion Battery	24.2 kW/h	100 kW	37,590 €
Tesla Model S	Li-Ion Battery	100 kW/h	193 kW	123,000 €

Table 2
The values and ranges of the different characteristics of the batteries that have been mentioned in the paper

Battery type	Pb-PbO_2	Ni-Cd	Ni-MH	Na-NiCl	Na-S	Li-Ion
Specific Energy (Wh/kg)	30-60	60-80	60-120	160	130	100-275
Energy Density (Wh/L)	60-100	60-150	100-300	110-120	120-130	200-735
Specific Power (W/kg)	75-100	120-150	250-1000	150-200	150-290	350-3000
Cell Voltage (V)	2.1	1.35	1.35	2.58	2.08	3.6

The different indices of these batteries are:

Volumetric Energy density: It indicates how much energy the battery can store. In the case of EVs, the diving range is dependent on the energy density of the battery. The energy density of batteries is measured as the energy that a battery can supply per unit volume and its unit is Wh/L or Wh/dm^3.

Gravimetric Energy density: It is a measure of how much energy a battery can store in comparison to its weight. It is measured in Wh/kg.

Power density: It indicates the battery's maximum output. For HEVs, which are fitted with a generator, the ability to supply power for acceleration is more important than the battery's capacity to store energy, and hence power density is more important in this case than energy density. Its unit is W/kg.

In addition to these indices, some of the characteristics of these batteries are:

Specific energy: The energy that a battery can provide per unit mass is known as specific energy of the battery. Its unit is Wh/kg. Its formula is given as:

[Nominal voltage (V) x Rated battery capacity (Ah)] ÷ Battery weight (kg)

Capacity: Battery capacity is defined as the maximum amount of energy stored by a battery and is the product of the current that can be extracted from the battery while it is still able to supply the load until its voltage is dropped lower than a certain value for each cell, under specified conditions. The commonly used units of battery capacity are Ampere hour (Ah) or watt hour (Wh), but the latter is most used while talking about electrical vehicles' batteries. The battery capacity is an extremely crucial aspect of an EV's battery because it directly influences the autonomy of the EV.

Internal resistance: The batteries' components are not perfect conductors, which means that they resist the transmission of electricity. Some energy is always dissipated during the charging process in the form of heat (thermal loss). The internal resistance will tend to have a greater impact on high power charges because the power lost due to resistance is equal to the heat generated per unit time. Lesser energy will be lost during slower charging processes as opposed to quicker charging processes due to this. Hence, batteries should support slow charging and higher temperatures induced due to the internal resistance, which also does not damage the battery and reduce the battery life as much as fast charging processes. The decrease of the internal resistance of the battery can reduce the charging time that is required, which is one of the most important drawbacks of the electrical vehicles' batteries today.

Efficiency: Battery efficiency can be divided into coulombic efficiency, voltage efficiency, and energy and power density. The coulombic efficiency is the ratio of the number of charges that enters the battery during the charging process to the number of charges that leave the battery during the discharging process. It is usually as high as 95%. The loss in efficiency is primarily due to secondary reactions in the battery, such as the electrolysis of water. The voltage efficiency is largely measured by subtracting the discharging voltage from the charging voltage.

Nominal Voltage: It is defined as the average voltage of a fully charged battery when delivering current at s pacific discharge rate. It is not the actual voltage of a battery. The actual voltage of the battery varies with the amount of charge present in it. As the battery discharges its actual voltage decreases, but the nominal voltage is characteristic of a battery and depends only on the type of battery.

These characteristics give an idea about the battery performance.

3. Summary and Conclusion

The paper discusses the different types of batteries used in electrical vehicles, their characteristics, and the comparison of these characteristics in different batteries and comparison of the models that use Li-ion batteries. It also mentions solid state batteries, which seem to be a better alternative for Li-ion batteries that are being used today.

Electrical vehicles are gradually replacing conventional fuel-based vehicles. However, they currently face a few major challenges that impede this inevitable switch to EVs. They are:

Charging, battery issues: EVs are powered by lithium-ion batteries. The design of these lithium-ion battery packs is limited by the size and mass of the pack. It is not feasible after a point to make the pack any bigger because it adds a lot of mass to the vehicle. The other aspects of the performance of the car begin to suffer, thus reducing the overall efficiency of the car. The greater the mass, the tougher it is to handle, accelerate, and decelerate the automobile.

Charging infrastructure and the driving range: For Electrical vehicles, there are three levels of charging.

Level 1- the car is charged by plugging the vehicle into a 120-

volt AC home outlet via an onboard charger. This takes 17 hours to charge the car. Level 2- The vehicle is plugged into a 240-volt power source at home or a charging station. This takes 3.5 to 7 hours according to Canaccord Genuity. Level 3- It is a DC fast charging unit based on a 480-volt system These charging units are not geared for home installation. Instead, consumers need to take the vehicle to a charging station. The stark contrast between conventional fuel vehicles and EVs is evident in reference to the time it takes to refuel a conventional vehicle and the time it takes to recharge an EV. Even in the United States there aren't many fast-charging stations, not to mention that most countries which use electrical vehicles do not have enough facilities to install level 2 charging stations. According to BBC, even though the range of most electrical vehicle models has improved significantly in the past few years, a limited driving range does pose a challenge to many drivers. Thus, only a few models of electric vehicles can be used for long distances such as cross-country trips.

Financial issues: A long standing problem with electrical vehicles has been the sheer cost of producing the vehicles and setting up the infrastructure for charging stations discourages both producers and consumers from transitioning from conventional fuel-based vehicles to EVs.

Electrical vehicles are not the future anymore; they are the present. As environmentally responsible citizens, we must gradually switch to electrical vehicles. Even though the disadvantages need to be overcome before everyone can switch to these vehicles, the benefits of electrical vehicles far outweigh any sort of disadvantage.

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