Current and Future Battery Technology

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Group 15, William Harper, Jacob Sickafoose, Casey Bender, Lisha Yao

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Abstract

With the vast variance of different battery types, this paper focus on why such a large selection of battery types exist and their applications. This paper specifically focuses on four battery types: lead acid, alkaline, lithium ion, and solid-state. For each battery type, we investigated what purpose each serves, their applications, benefits and drawbacks, as well as took a look at the chemistry and safety. In addition to looking at the current state of each battery technology, and batteries in general, we discuss what direction the future of batteries is going. At the end of the paper, we present our finding as to why each battery is used and what applications they best serve.

1 Introduction

Batteries are a part of everyday life now. It would be hard to imagine going a day without batteries to support the various devices and vehicles that we have become used to. They have become a ubiquitous part of our culture. When we drive our car to the store or call our family on our mobile phone, batteries are the chemical energy storage that make this possible. Unconsciously, we rely on batteries to run some very important functions of our lives.

A battery is a container consisting of 1 or more cells, in which chemical energy is converted into electricity and used as a power source. The term battery and cell are often used interchangeably, but typically cells are the individual energy units with positive at one end and negative at the other. A battery would be a collection of these cells. For example the Tesla PowerPack (not to be confused with PowerWall) uses the 18650 cell. This cell model has been a standard for electronics like laptops and power tools for some time now. The PowerPack module provides 100 kWh of energy and contains 8256 cells per pack, each 18650 cell providing approximately 12.1 kWh of energy. This pack is also broken down into modules, which have 516 cells per module. This makes replacing the batteries much easier since you do not have to replace a pack containing 8000+ cells, just replace the smaller module with 500 cells leaving the functioning 7500 cells in place [1].

There are many different types of batteries and cells on the market today. These are differentiated by the chemicals used for cathodes/anodes, the size/shape of the cell and the discharge rate among other qualities. Even within the same type of battery, like lead acid batteries, there are variations in this type like the starter battery and deep cycle battery. One of these can put out a high amount of energy in a short period of time the other puts a low amount of power over a long duration. Given these differences this paper seeks to establish why there are so many variations in battery technology by analyzing the most popular battery technologies available today and the near future.

2 Problem Statement

There are many different types of batteries that ultimately satisfy the same function of chemical energy storage. For example, an electronic device could be powered by a lithium ion cell just as easily as as alkaline cells. The energy capacity between the two could be the same, but why would one cell be preferred over the other? Which characteristics of that cell make it the optimal choice for that situation?

Choosing the right battery is very important when it comes to your final product. Look at what happened with Samsung's Galaxy Note 7. Samsung chose to use a lithium-ion cell in their product which can be prone to explosions when the cell is damaged. In the case of the Note 7, some of the cells were not damaged, but still managed to explode. Even with this difficulty in safety, li-ion batteries are still the preferred method of powering mobile phones. With the problem that this technology presents why is it still used for this application and becoming more popular in other applications?

Given these differences this paper seeks to establish why there are so many variations in battery technology by analyzing the most popular battery technologies available today and the near future. 4 types of batteries will be focused on over the course of this paper: Lead-acid, Lithium Ion, Alkaline and Solid State batteries.

3 Technical Solution

In this section, the description of battery technologies are included along with their optimal applications.

3.1 Lead Acid

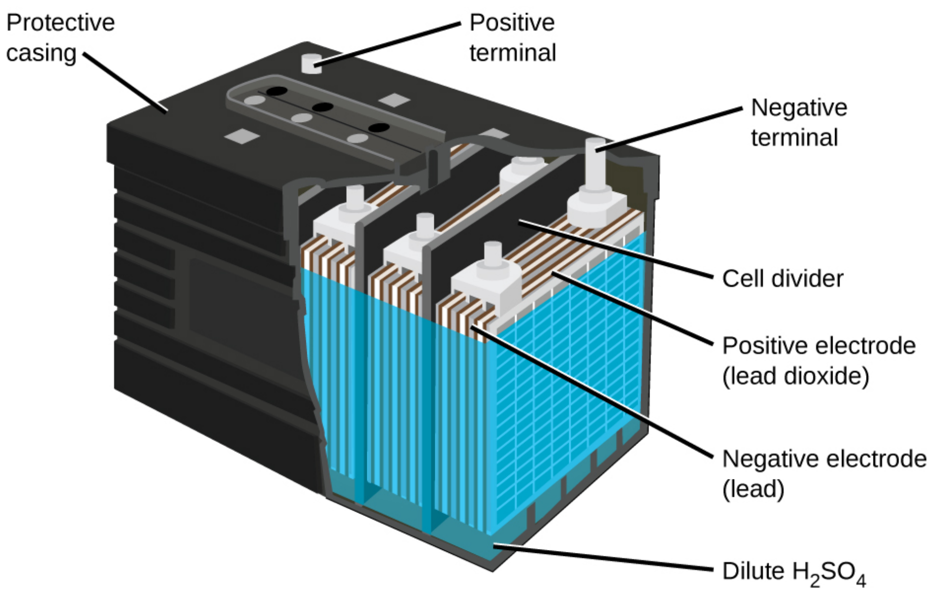


Figure 1: Lead Acid Battery Structure [2]

The lead acid battery is the first rechargeable battery and one of the oldest types of battery. They were invented in the 19th century and today, they are sold worldwide. Lead acid batteries are commonly used to power cars, automobiles and other applications. They are typically made with lead sulfate plates and sulfuric acid. Two common types of lead acid battery include the starting battery and the deep sleep battery. As a starting battery, lead acid batteries have a short discharge and therefore, they are popularly used to start cars. As a deep sleep battery, they have regular to frequent discharge. Example applications of lead acid batteries as deep sleep batteries include electric vehicles, photovoltaics, and power supplies. Lead acid batteries are still popular today as they are inexpensive to manufacture and best for the long term usage.

Cycle performance on these batteries depends on depth of discharge (DOD) [3]. The higher the depth of discharge, the lower the life cycle. For the starter battery, at 100% DOD, it can go up about 15 cycles (2). At 30% DOD, the starter battery can go to about 150 cycles. Deep cycle batteries are constructed for maximum capacity and made with thicker lead plates. Therefore, they have a longer life cycle compared to the starter battery. For the deep cycle battery, at 100% DOD, they can last up to 200 cycles, At 30% DOD, they can go to about 1000 cycles or more. These are just statistics from the typical lead acid battery. In today?s day and age, there are advances in lead acid storage technology that furthers the life cycle of lead acid batteries even more.

Lead acid batteries share the same basic chemistry [4]. The positive electrode of lead acid batteries is made of lead-dioxide, PbO2. On the other hand, the negative electrode is made of metallic lead. Charging lead acid batteries is composed of three stages [5]. The first stage of charging consist of the constant current constant voltage (CC/CV) charge method. The lead acid is charged with a bulk of constant current. The second stage consist of a constant lower current which provides saturation. This is also known as topping charge. The third and final stage is float charge which makes the battery maintain its state of being fully charged. These stages are depicted in Figure 2.

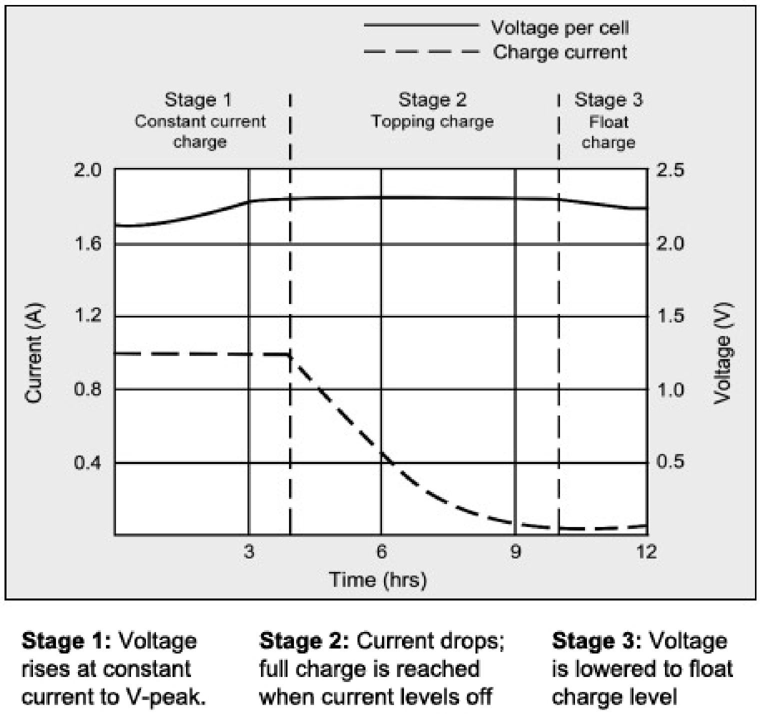


Figure 2: Charging Stages of Lead Acid Batteries [6]

There are typically have two types of lead acid batteries storage technology. One type being lead acid carbon technology and the other type being advance lead acid carbon technology. From the name, lead acid carbon technology are lead acid batteries made with the inclusion of carbon. With carbon technology, these batteries improve in their power characteristics and their state of charge. Compared to regular lead acid batteries, lead acid carbon batteries have faster recharge rates, longer life cycle and require less maintenance.

As for environmental concerns, lead acid batteries are one of the most recycled batteries out there . Recycling and disposing these batteries is an important part of their life cycle. The batteries are recycled by taking them apart for their components. Then, the lead plates and grid are smelted to be reused in making new batteries. Other components are also recycled. One of the advantages of this is that most new batteries are made from recycled material.

In summary, there are advantages and advantages for lead acid batteries. The disadvantages include limited life cycle, fully saturated charge can take up to 14 to 16 hours, and poor weight to energy ratio. However, their advantages to these batteries is that they are inexpensive to make, they have low cost per watt hour, they are sold worldwide, they have the lowest self discharge among rechargeable batteries and that they can be recycled and from those recycled material, made into new batteries. Overall, lead acid batteries have came a long way since its introduction.

3.2 Alkaline

Alkaline batteries are the most widely used type of batteries used in the world. Alkalines power most personal and household electronics that rely on battery power, such as remote controls, clocks, handheld gaming systems and radios. These types of batteries are non-rechargeable, high energy density, batteries that have a long life span that are designed for long lasting performance making them the ideal battery type for powering said type of electronics.

Alkaline batteries come in various sizes such as AAA, AA, C, D, 9 V and more, each of which support different application and can immediately be used after purchase as they do not require charging, this make alkalines idea to use even during emergency situations. Additionally, the shelf life for alkanes ranges from three to four years, give this longevity it allows alkaline batteries to be stored for long periods in time in things such as emergency kits.

Another advantage alkaline batteries have over other types of batteries is that they have higher energy density. Akalines have double the energy density of a Leclanchè cell and zinc-carbon batteries. This allows the battery to produce the same energy while lasting longer than other batteries. Alkaline batteries "have a steady voltage offering better energy density and leakage resistance than carbon zinc batteries. This is mainly due to the manganese dioxide anode material, which is purer and denser, thereby reducing the space taken up by internal components" [7]. Most of the market participants have shifted their focus on rechargeable chemistries such as nickel metal hydride and lithium-ion.

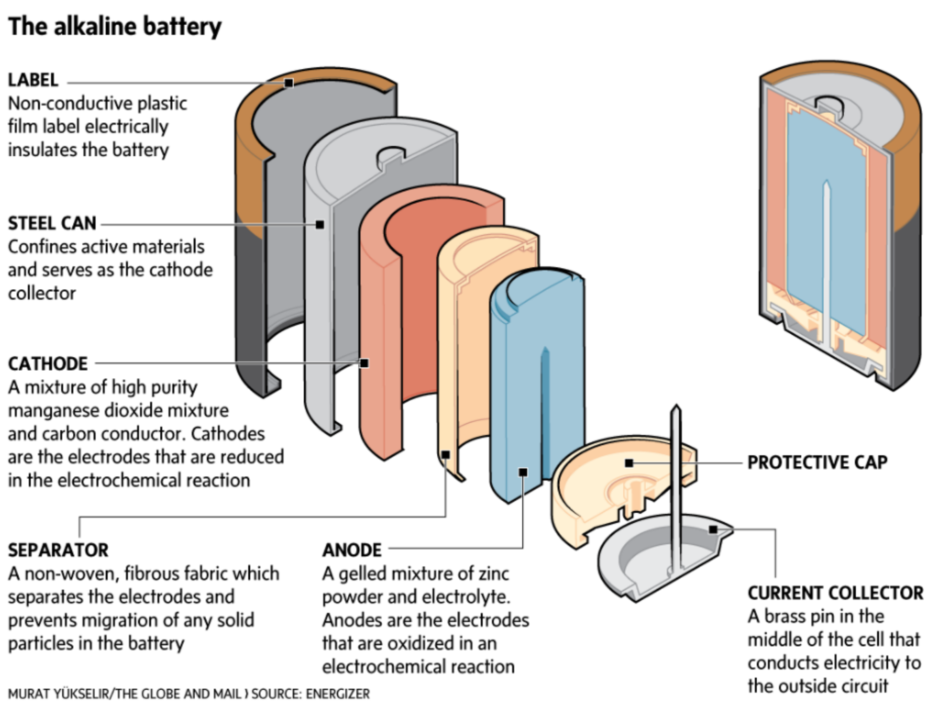


Figure 3: The Alkaline Battery [8]

Alkaline batteries are made with an alkaline electrolyte of potassium oxide instead of ammonium chloride or zinc chloride, both of which are acidic components. They have a higher energy density, and therefore a longer shelf life, without compromising on voltage. Alkaline batteries can be disposable or rechargeable and are generally 1.5 volts per cell and are available in various sizes.Typically, in a cylindrical alkaline battery, manganese dioxide powder is mixed in a gel with carbon powder to increase conductivity, and is the positive electrode in a stainless steel can. The center rod or the negative electrode is usually powdered zinc in a gel electrolyte of potassium hydroxide. A porous cellulose or polymer membrane is the separator between the two electrodes for ion transport. The quality of the various components and purity of the chemicals are the major reasons for capacity and long term reliability.

In an alkaline battery, the negative electrode is zinc and the positive electrode is manganese dioxide. "The alkaline electrolyte of potassium hydroxide is not part of the reaction, only the zinc and MnO_2 are consumed during discharge. The alkaline electrolyte of potassium hydroxide remains, as there are equal amounts of OH^- consumed and produced."[9]

The half-reactions are:

$$Zn_{(s)} + 2OH^-_{(aq)} \rightarrow ZnO_{(s)} + H_2O_{(l)} + 2e^- \; [E_{oxidation}{}^\circ = +1.28\text{ V}]$$

$$2MnO_{2(s)} + H_2O_{(l)} + 2e^- \rightarrow Mn_2O_{3(s)} + 2OH^-_{(aq)} \; [E_{reduction}{}^\circ = +0.15\text{ V}]$$

Overall reaction:

$$Zn_{(s)} + 2MnO_{2(s)} \rightleftharpoons ZnO_{(s)} + Mn_2O_{3(s)} \; [e^\circ = +1.43\text{ V}]$$

Alkaline batteries are friendly to the environment as they are disposed in the trash, they do not special recycling like many other battery types. Moreover, the environmentally friendly reputation appeals to consumers who are conscious about polluting the environment.

3.3 Lithium Ion

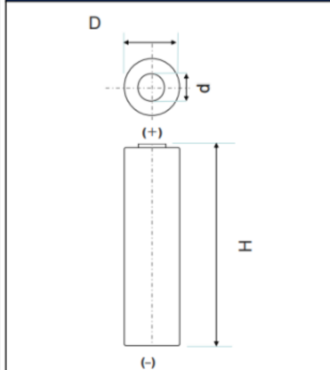
Li-ion technology is a fast growing energy storage platform. It can can be used in applications ranging from electric vehicles to cell phones. This type of battery could replace lead-acid or alkaline batteries where they are used. Given the configuration of the li-ion cells, this type of battery could function for a short duration with a high output like a vaporizer, or at a lower current for a longer duration like a deep cycle battery bank.

Specifications

Rated capacity(1)		3300mAh
Capacity(2)	Minimum	3350mAh
	Typical	3450mAh
Nominal voltage		3.6V
Charging	Method	CC-CV
	Voltage	4.20V
	Current	Std. 1475mA
	Time	Std. 270 min.
Weight (max.)		48.0g
Temperature	Charge	10 to +45° C
	Discharge	-20 to +60° C
	Storage	-20 to +50° C
Energy density(3)	Volumetric	693 Wh/l
	Gravimetric	224 Wh/kg

(1) At 20° C (2) At 25° C
(3) Energy density is calculated using bare cell dimensions (without tube).

Dimensions



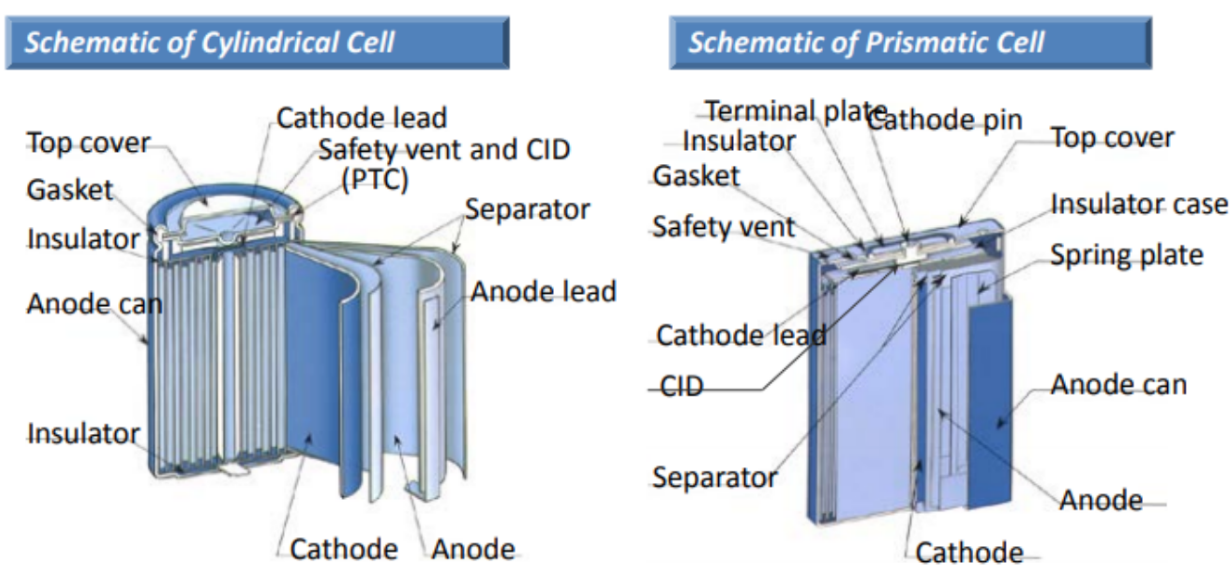
With tube	H	Max. 65.30mm
	D	Max. 18.50mm
	d	Max. 9.0mm

When designing a pack, refer to the cell's mechanical drawing for precise dimensions.

Panasonic

Li-ion cells are able to supply these devices with with a large amount of current when assembled into a battery. This style of battery has a very high level of energy density. The Panasonic 18650 cell has a rated volumetric energy density of 693 Wh/l and Gravimetric density of 224 Wh/Kg. Compare this to a lead acid cell from Power Sonic [10]. This cell has a volumetric energy density of 90 Wh/L and a Gravimetric density of 35 Wh/kg [11]. Comparing these two options, it would take far fewer cells to provide the same amount of power. This feature makes Li-ion technology perfect for small, portable electronics with high power demands. Battery makers use what is called a prismatic style cell in order to pack this powerful battery into a small flat, rectangular form which we find in cell phones and laptops today. If Tesla decided to go with deep cycle lead-acid batteries to power their vehicle it would not perform nearly as well in terms of horsepower and speed. The Li-ion cell is able to deliver more power, in a shorter duration allowing the electric motors to run faster. Also, like mentioned above, the weigh would be much greater due to the lower energy density. The expensive Li-ion cell is what allows the Tesla to have the spectacular performance that it does, keeping the performance high and the weight low [12]. This applies to electronics as well. In the 90's handheld game systems took 6+ batteries and would use the energy in them in less than an hour. It would be impractical to expect cell phone users to keep multiple pounds of batteries with them.

Previously stated in the introduction, the Tesla PowerPack is found in the Tesla Model S, X and 3. This pack has a capacity of 100 kWh of energy which is required to power the 60 motors that make the car run beautifully like it does. With this amount of energy the Tesla is able to travel approximately 250 miles before needing to recharge. In order to travel about 250 miles it requires about 8500 batteries that are fully charged. These 8500 batteries do not come at a cheap cost. Their compact form factor and high energy density come at a comparatively high cost than other batteries and energy storage that perform similar tasks. If you pay below the consumer average at $5 a piece then you are looking at $42,500 roughly [13]. To travel 250 miles in a gasoline powered vehicle that averages 35 mpg paying 3.25 a gallon for gas, then you only spend about $25. With this simple example, it is easy to see how costly any type of lithium-ion system would be to purchase compared available alternatives. This has has been a preventative factor in the adoption of this type of technology in the past, but with Elon's new Giga-factories the price of lithium-ion cells is likely to significantly drop.



[14]

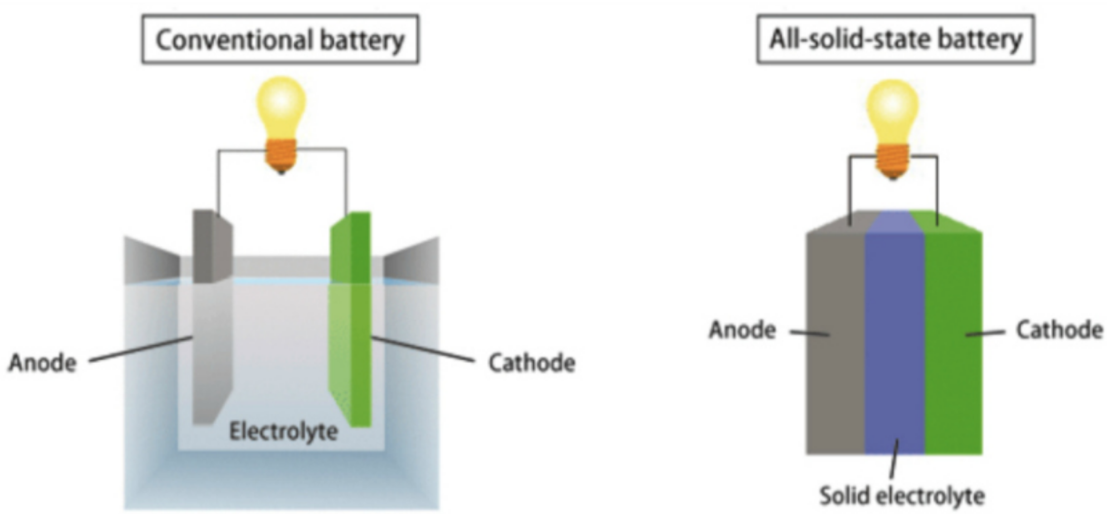
The great benefits of these cells come at a cost though. Li-ion cells are prone to combustion when the cells become damaged. A typical cell of this type resembles a spiral cake, with cake and cream separated by layers. If these layers bend or make contact with similar layers, it's going to be a bad day. Like stated in the introduction Samsung ran into this very issue. The batteries produced for that particular product had a flaw that caused the layers of the battery that must stay separate, to make contact. Other ways for the battery to fail are through poor battery maintenance and charging. There are many example on the web today showing li-ion cells combusting in individuals faces, hands and pockets causing damage. These accidents come from a lack of understanding of how the cell should be charged and discharged. Ignorant users will try to make their 18650 cell perform past its specified rating and causing stress on the cell leading to failure [15]. These cell are also causing issues in car accidents involving Teslas. Every accident involving a Tesla has the capacity to fail and catch fire. Many situations like this have been reported which is a concern to all who use the roads [16].

Along with safety concerns to the consumer, there are also concerns about the materials that make up li-ion batteries. One of the main components making up this type of battery is cobalt. The main sources of this material is from mineral deposits mined by hand in parts of Africa like the DNRC. Cobalt is often referred to as a conflict mineral because the behaviors that surround the act of mining the minerals. These highly desirable minerals lead to poor conditions for the people working there and even fighting between those who want the materials the most. The mining of these materials often lead to the funding of radical and extreme ideas [17].

Li-ion cells are very popular today and probably won't go anywhere in the near future. Looking at the facilities that Elon Musk has built and is planning on building, he obviously believes in li-ion enough to invest in a number of multi billion dollar facilities. Given the cost of the battery currently these facilities will hopefully reduce the cost of this cell and allow more consumers to invest in the technology.

3.4 Solid-State

Solid-state batteries are a type of battery that is still under development. They consist of a solid electrolyte, rather than a liquid which gives them a completely solid construction.



Some of the world's top companies, such as Samsung and Dyson, are currently trying to bring solid-state batteries to the main consumer market. Solid-state batteries are scheduled to be used everywhere lithium-ion is used today, after their problems have been corrected. Currently, solid-state batteries have poor low temperature performance, and they are very expensive to manufacture. Companies are still testing with different materials, trying to find the perfect combination which is cheap and effective.

Solid-state batteries are having large amounts of money invested in their development because they have the potential to be better than Lithium-ion in every way. Solid-state batteries are capable of having higher energy densities and faster charging than Lithium-ion. In addition to this, because of their solid design, they can be made into almost any shapes. This will allow them to be fit into any compartment in any device. Device makers can be as efficient as possible at storing power, to make sure they can fit the most. This is unlike their liquid counterpart, whose design must include an encasement to hold the liquid electrolyte.

One of the largest problems with lithium-ion is that they must be made of flammable materials and provide a safety risk. Solid-state batteries do not need to be made out of dangerous materials, and are not at risk of leaking battery acid after rugged use. They are not at risk of blowing up, while holding a charge. This is one of the main reasons why they will probably replace lithium-ion batteries. As we use technology more and more in our daily lives, it becomes more of a concern having potential bombs in our pockets, on our wrists, or under our cars. Of course lithium-ion cell monitoring technology has come a long way since the start, but the risk is always there. Solid-state batteries in the future may cost more than Lithium-ion, but the extra cost will be spent in applications where safety is a necessity.

One small Massachusetts company, named "Ionic Materials", has claimed to be close to a successful solid-state battery. They have created a new material. It is a liquid crystal polymer, which they claim, solves three of the main issues with Solid-state batteries. For one thing, their batteries are now capable of operating at as low a temperature as room temperature. Most solid-state batteries can only work at temperatures around 60°C. Their polymer is also allows ions to move across it as fast, if not faster, than in an everyday Lithium-ion cell. Lastly, they can be made cheaply. The main hurdle of developing solid-state batteries has been finding a material with all the perfect qualities. If this liquid crystal polymer works out, we could be close to solid-state batteries [18].

4 Conclusion

After our research, we have found that the large range of applications for batteries made a large amount of variances necessary. Batteries play many important roles in all of our everyday lives. With roles so important and diverse, the batteries must be extremely specialized to achieve the best performance possible in every situation. Batteries must be reliable and perform as exactly as expected. We only looked at four different types of batteries but there are many more. Lead acid batteries have been around the longest. As a result, they are a well explored technology and very reliable. They are used as car batteries because they do not mind being discharged and recharged all the way, many times. This property also allows them to be used for solar storage. Alkaline batteries are the go to battery type for disposable, batteries. They primarily power small consumer electronics because they are capable of holding their charge for long periods of time and they provide low voltages. Lithium ion batteries are utilized in roles where their much higher energy density and fast recharge rates are needed. Batteries that hold high power, and have less mass, are needed in smartphones, laptops, electric cars, and many more devices. Solid-state batteries are not practical yet for wide spread consumer use, but the hope is that they will replace lithium ion. Lithium ion technology is still being developed to increase energy density and recharge speeds, but solid-state batteries have already proven that they have a much better potential. Batteries are a necessary part of life, and they must be as cheap, reliable, and effective as possible. Development will continue to happen and batteries will continue advancing, and achieving ever higher results.

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